Technology
Development
Program Plan

VOLUME I–
Missions

DTIC QUALITY INSPECTED 4

PLEASE RETURN TO:

BMD TECHNICAL INFORMATION CENTER
BALLISTIC MISSILE DEFENSE ORGANIZATION
7100 DEFENSE PENTAGON
WASHINGTON D.C. 20301-7100

The technology developed toda

The Decade of Discovery in Astronomy and Astrophysics
National Research Council

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

19980309 073

Accession Number: 6340

Publication Date: Mar 26, 1993

Title: AstroTech 21. Volume I: Missions

Corporate Author Or Publisher: NASA

Comments on Document: from BMDO/DE

Abstract: In 1989 the Astrophysics Division of NASA Headquarters initiated AstroTech 21, a joint program of the Office of Advanced Concepts and Technology to lay the technological foundation for its scientific program for the 21st century. Recommended initiatives include: Space Infrared Telescope Facility (SIRTF); Stratospheric Observatory for Infrared Astronomy (SOFIA); Astrometric Interferometry Mission (AIDM0; optical and infrared interferometry in space; technology for the next generation observatories, including large telescope technoloy; submillimeter receiver and telescope technology; and high energy mirror and detector technology.

Descriptors, Keywords: AstroTech 21 mission implementation technology transfer continuous flight SOFIA explorer HST Hubble telescope instrument SIRTF SMIM/FIRST AIM lunar astrophysics relativity gravity radio astronomy spacecraft sensor optics interferometry

Pages: 188

Cataloged Date: Jan 07, 1998

Copyrighted or Not: NO

Document Type: HC

Number of Copies In Library: 000001

Record ID: 46058

Source of Document: BMD

AstroTech 21

Volume I

Missions

Technology Development Program Plan

for the U.S. Space Astrophysics Program

by the Astrophysics-Technology Team

Astrophysics Division / Office of Advanced Concepts and Technology

NASA Headquarters

March 26, 1993

U 6340

Contents

Volume II

NOTE CONCERNING BUDGET FIGURES CONTAINED IN THIS PLAN

The budget figures listed in this plan refer to the resource requirements to implement the described AstroTech 21 program.

The resource requirements referring to future years DO NOT necessarily reflect actual budgets that are contained within NASA's current plans.

Executive Summary

The technology developed today is used in the science of tomorrow.

Decade of Discovery in Astronomy and Astrophysics, Astronomy and Astrophysics Survey Committee, National Academy of Sciences, 1991

The process by which the Astrophysics Division determines its technology needs is highly developed, institutionalized, and intimately tied to its AstroTech 21 Program

Improving Technology for Space Science, Committee on Space Science Technology Planning, National Academy of Sciences, 1993

In 1989, the Astrophysics Division of NASA Headquarters initiated AstroTech 21, a joint program with the Office of Advanced Concepts and Technology (OACT), to lay the technological foundation for its scientific program for the 21st century.

In its planning of AstroTech 21, the Astrophysics Division was guided by the recommendations of a National Academy of Sciences survey of the astronomical sciences in the 1990s, published in 1991 under the title *The Decade of Discovery in Astronomy and Astrophysics* (often referred to as the "Bahcall Report"). The recommendations for NASA include the following scientific and technological initiatives:

- Science
    - Space Infrared Telescope Facility (SIRTF)
    - Stratospheric Observatory for Infrared Astronomy (SOFIA)

- Astrometric Interferometry Mission (AIM)

- Technology
    - Optical and infrared interferometry in space
    - Technology for the next generation observatories, including large telescope technology
    - Submillimeter receiver and telescope technology
    - High energy mirror and detector technology

In addition to the Bahcall Report, the Astrophysics Division was guided by the principle that there is a strong interdependence between science and technology. Scientific advances frequently enable new technologies, while new technology is often the basis for scientific discoveries.

These guiding principles lead directly to the goals of AstroTech 21:

- To identify the future technology needs of the Astrophysics program; and

- To formulate detailed technology plans for the development of necessary technologies.

The first goal is absolutely fundamental; the science community needs to clearly identify its technology development requirements in order for NASA to properly direct its technology development investments. The second goal is a technological "road map" for the future -- a detailed technology investment strategy for NASA for the space Astrophysics program.

The benefits of AstroTech 21 are manifold. First, the science community and NASA benefit because (1) by investing early and adequately in science missions' critical technologies, high technology items are removed from the critical path for development; (2) the risks of cost overruns and slippages in schedule are reduced; and (3) the missions' scientific productivities are enhanced. Without such early and adequate planning, the "better, faster, cheaper" paradigm cannot be followed.

Second, OACT wins because (1) its AstroTech 21 implementation activities support one of NASA's principal goals -- advancing Space Science, (2) the technology is useful and readily transferable, and (3) the science community will become an advocate of OACT programs.

And third, the country benefits because (1) Astrophysics flight programs will be implemented faster, at lower cost, and with better results; and (2) AstroTech 21 contributes to the U.S. technological base. As described further in section I.C, AstroTech 21's technology efforts contribute at present to nine of twelve "Emerging Technologies" identified by the Department of Commerce as having the potential to advance substantially national productivity and quality.

Hundreds of experts from NASA field centers, DoD and other national laboratories, universities, and industry have participated in the development of the AstroTech 21 plan. These planning activities have been carried out principally through workshops and working group meetings. The results have been published as proceedings and detailed technology plans for specific future Astrophysics missions, such as for SOFIA, SIRTF, SMIM/FIRST, and AIM.

To ensure that the activities of AstroTech 21 are refined and successfully implemented, the Astrophysics Division and OACT assembled the Astrophysics-Technology Team (ATT). ATT's charter and the current ATT membership follow the Executive Summary.

AstroTech 21 is an evolving program. As space astrophysics evolves, so do plans for future missions and related technology needs. Mature technologies will transition out of the AstroTech 21 program, and new ones will be added. AstroTech 21 workshops and meetings will continue to be conducted; and the plans will be updated.

This document describes the current state of the AstroTech 21 program.

The following table lists the tasks and resource requirements to implement the AstroTech 21 program. The resource requirements referring to future years do not necessarily reflect actual budgets that are contained within NASA's current plans:

NASA's Astrophysics Technology Needs: AstroTech 21

(Millions of Real Year dollars)

Need Level	*AstroTech 21*	FY93	FY94	FY95	FY96	FY97	FY 98
Highest-Priority Nearest Term Needs	**Airborne Astronomy Technology (SOFIA)**						
	Shear Layer Control & Wind Tunnel Testing	1.50	2.57				
	Cavity Acoustic Quieting Technology	0.20	1.05	1.10			
	Lightweight Optics Demonstration	2.50	6.30	7.17	3.47		
	Isolation & Support Technology	0.80	6.30	5.84			
	Intelligent Operations	1.85	3.90	4.60	3.17		
	Sub-Total	**6.85**	**20.12**	**18.71**	**6.64**		
	Infrared Technology (SIRTF)						
	Detectors & Instrument Technology	5.00	4.20	2.21			
	Integrated Instrument Module Test-Bed	3.00					
	Cryogenic Spacecraft Technology	5.00	5.25	2.21			
	Cryogenic Optics Technology and Test Facility	6.00	3.62	4.69	1.93	0.22	
	Instrument Development		26.25	49.61	71.66		
	Sub-Total	**19.00**	**39.32**	**58.71**	**73.59**	**0.22**	
High Priority Mid-Term Needs	**Submm Technology (FIRST/SMIM)**						
	Heterodyne Receivers	5.60	6.30	6.89	8.10	8.51	7.66
	Lightweight, Segmented Reflector Prototype	1.50	2.63	4.96	4.05	1.82	1.28
	Sub-Total	**7.10**	**8.93**	**11.85**	**12.16**	**10.33**	**8.93**
	Interferometer Technology (AIM)						
	Controls-Structures Interaction	2.00	4.73	4.96	4.63	4.38	
	Metrology	1.00	3.15	3.31	3.47	3.65	3.83
	Active Delay Lines	0.50	2.10	2.21	2.32	2.43	2.55
	Ultra-precision Deployable Structures	0.50	1.05	1.10	1.16	1.22	1.28
	Vibration Isolation Systems	0.50	0.53	1.10	1.16	1.22	1.28
	Sub-Total	**4.50**	**11.55**	**12.68**	**12.73**	**12.88**	**8.93**
	UV/Visible Technology (HST 3rd Generation Instruments)						
	CCDs (Front and back illuminated CCDs & controller technology)	0.50	0.63	0.66	0.58		
	Solar Blind Detectors and/or Filters	0.40	0.53	0.55	0.46		
	Sub-Total	**0.90**	**1.16**	**1.21**	**1.04**		
Important Far-term Needs	**Mission-specific, Far-term Term Needs**						
	Lunar Astrophysics Technology (LUTE)	0.15	0.26	0.55	1.16	3.04	6.38
	Relativity / Gravity Physics Technology (LAGOS)	0.15	0.26	0.55	0.87	1.22	3.19
	Sub-Total	**0.30**	**0.53**	**1.10**	**2.03**	**4.25**	**9.57**
Continuous Critical Needs	**Ongoing Technology Needs***						
	Sensors Technology	1.00	1.58	2.76	5.79	9.12	12.76
	Optics Technology	2.50	3.15	5.51	9.55	12.16	19.14
	Spacecraft Technology**	5.00	7.88	11.03	11.58	12.16	12.76
	Mission Operations Technology	2.00	4.20	5.51	8.68	12.16	12.76
	Sub-Total	**10.50**	**16.80**	**24.81**	**35.60**	**45.58**	**57.43**
	Total Needs	**49.15**	**98.40**	**129.07**	**143.79**	**73.27**	**84.87**

* Also address the technology development needs of 2 of the 3 TOPS-1 mission candidates for Code SL

* Addressing these needs will benefit the rest of the Astrophysics Program, i.e., sub-orbital missions, Explorers and International Missions-of-Opportunity, and Explorers. Level of need based on Astrotech 21 program studies.

** "Placeholder" for needs to be identified at upcoming Astrotech 21 Spacecraft Technology Workshop. Needs likely to include such items as gyros, on-board data storage, precision frequency standards, batteries high frequency RF transponders, and autonomous star trackers.

Charter

Astrophysics-Technology Team
(ATT)

Astrophysics Division / Office of Advanced Concepts and Technology

NASA Headquarters

March 25, 1993

The Astrophysics-Technology Team (ATT) is a team constituted jointly by the Astrophysics Division (Code SZ) and the Office of Advanced Concepts and Technology (OACT) to ensure that the technology needs of Astrophysics are defined, prioritized, communicated, successfully developed and implemented, and infused into flight programs.

Membership

Astrophysics-Technology Team (ATT)

March 25, 1993

Office of Advanced Concepts and Technology (Code C)

- **Samuel L. Venneri or TBD, Co-Chair**
- **Steven C. Hartman, Program Planning & Integration Division**
- **Robert J. Hayduk, Spacecraft & Remote Sensing Division**
- **Gordon I. Johnston, Spacecraft & Remote Sensing Division**
- **Melvin D. Montemerlo, Spacecraft & Remote Sensing Division**
- **Lelia Vann, Flight Projects Division**
- **Member TBD, Advanced Concepts Division**

Astrophysics Division (Code SZ)

- **Michael S. Kaplan, Co-Chair, Advanced Programs Branch**
- **David A. Gilman, Explorer Programs Branch**
- **Robert V. Stachnik, UV/Visible/Gravity Branch**
- **Peter B. Ulrich, Observatories Development Branch**

FY 93 Critical
Astrophysics Technology Needs

February 23, 1993

(revised 3/18/93)

Mike Kaplan

Chief, Advanced Programs Branch

Astrophysics Division

NASA Headquarters

Overview of Critical Needs

- Needs are time critical due to programmatic decisions that need to be made
- The existence of a technology program would have a significant impact on these programs
- Resolution of most of these needs is required by the end of February; other needs can wait until later this fiscal year
- Examples:
  - SOFIA lightweight optics, rotational bearing, shear layer control and "intelligent operations"
  - SIRTF detector arrays, cryogenic optics and cryogenic sensor readouts
  - FUSE detectors and optics testbed
  - Submillimeter aperture technology
  - Interferometry test-bed

Astrophysics Strategic Plan

	Flagship Missions	Intermediate / Moderate Profile Missions	Small Missions	Research and Technology Enhancements	Mission From Planet Earth
1994					
1995			UNEX Augmentation	SOFIA	
1996			International Collaboration Augmentation		
1997	SIRTF				Lunar Transit Telescope
1998	Astrometric Interferometry Mission	Far Infrared Space Telescope / Sub-millimeter Intermediate Mission			
	Greater Observatories e.g., Next Generation Space Telescope; Very High Throughput Facility; Large Deployable Reflector	NAE*			
2005		Intermediate Mission Three**			Lunar Interferometer

* = US-only Nuclear Astrophysics Experiment if joint ESA/NASA Integral Mission is not selected by ESA in Spring 1993

** = Selection of missions based on peer review from Announcement of Opportunity

2/10/93

Critical Needs

- Stratospheric Observatory for Infrared Astronomy (SOFIA)
- Space Infrared Telescope Facility (SIRTF)
- Near-Term Explorers: Far Ultraviolet Spectroscopy Explorer (FUSE)
- Submillimeter astrophysics
- Astrometric Interferometry Mission (AIM)

SOFIA Needs

- Shear layer control system for open cavity
  - Boundary layer diverter
  - Ramp in aft section of the open cavity
  - Cavity door
  - Active acoustic quieting devices
- Large spherical air or magnetic bearing for telescope assembly rotational suspension system
- 2.7 m, f/1.4 lightweight primary and associated optics
- Artificial intelligence tools to reduce observatory operations costs

Impacts of Code C Technology Investment on SOFIA

- Application of new, innovative technology can lower development risk and cost, while simultaneously enhancing the science and lowering operations costs
  - Lighter telescope reduces development cost and risk on rotational bearing
  - Quieter cavity reduces environmental specs of telescope, resulting in reduced development risk and cost on the telescope assembly
  - Shear layer control concept optimized to minimize drag and maximize seeing can enhance the scientific return while lowering operations costs
- SOFIA can serve as a "test-bed" for new mission operations technology
  - Link with AI group at ARC could focus technology program efforts to reduce manpower needed for mission operations; benefit most space science flight programs
- Removal of high tech items off the critical path for development

SOFIA Plan

$M	FY 93	FY 94	FY 95	FY 96	Totals
OACT Needs					
Shear Layer Control	1.50	2.45			**3.95**
CFD & Wind Tunnel Tests					
Cavity Acoustic Quieting*	0.20	1.00	1.00		**2.20**
Spherical Bearing / Isolation	0.80	2.30	5.30		**8.40**
Lightweight Optics	2.50	6.00	6.50	3.00	**18.00**
"Intelligent" Operations*	1.85	3.90	4.60	3.17	**13.52**
Totals	**6.85**	**15.65**	**17.40**	**6.17**	**46.07**
Astrophysics Plans					
Definition	1.50	3.00			**4.50**
Technology	0.39	0.50			**0.89**
Development			31.19	39.00	**70.19**
Totals	**1.89**	**3.50**	**31.19**	**39.00**	**75.58**

*=Preliminary resource estimate

SIRTF Needs

- Infrared focal plane array technology
  - Detector arrays in four bandwidths, 2.5 - 200 μm
  - Cryogenic, low noise readout technology
- Cryogenic optics technology
  - 1 m class, lightweight primary mirror for operation at liquid He temperatures
  - Technology for stray light control
- Cryogenic spacecraft technology
  - Concepts, components and test methodology for spacecraft using superfluid He, i.e., cryogenic spacecraft test-bed
  - Pointing and control technology calibrated to 3 arcsec
  - Inertial sensing and fine-guidance to 0.25 arcsec, stable for 1000 sec
- Instrument technology
  - Optical components, e.g., special filters, reliable at superfluid He temperatures
- Information systems technology
  - Less costly and more capable ground systems and operations
  - Tools to assist in observation planning, simulate observatory, provide "quick-look" Level 1 science requirements, and optimal level of on-board data compression

SIRTF Plan

$M	FY 93	FY 94	FY 95	FY 96	FY 97	Totals
OACT Needs						
IR Focal Plan Arrays*	2.92	3.42	2.37	1.27	0.50	**3.95**
Cryogenic Optics	2.18	3.03	3.00	1.15	0.50	**2.20**
Cryogenic Spaceccraft Test-bed	0.30	3.20	3.90	2.90	1.00	**8.40**
Instrument Technology	0.50	1.40	0.40	3.00	1.00	**18.00**
Information Systems	0.30	0.80	1.30	1.30	0.50	**3.00**
Totals	**6.20**	**11.85**	**10.97**	**9.62**	**3.50**	**35.55**
Astrophysics Plans						
Definition	0.15	1.00	4.00	10.00		**4.50**
Technology	7.85	7.00	6.00	5.00		**0.89**
Development					150.00	**70.19**
Totals	**8.00**	**8.00**	**10.00**	**15.00**	**150.00**	**75.58**

*=Includes $0.97 in current plan for FY 93 thru 96

FUSE Needs

- Optics technology
  - Highly deterministic mirror fabrication processes for FUSE as well as for other future UV and X-ray optics technologies
- Sensor technology
  - Prototype high-resolution far-UV spectroscopy detector and hybrid electronics to demonstrate performance for FUSE and other future missions

FUSE Plan

$M	FY 93	FY 94	FY 95	FY 96	Totals
OACT Needs					
Optics Technology	0.3	0.5	0.7	0.5	**2.0**
Sensor Technology	0.7	0.6	0.7	0.5	**2.5**
Totals	**1.0**	**1.1**	**1.4**	**1.0**	**4.5**
Astrophysics Plans					
Definition	4.8	5.0			**9.8**
Development			12.5	36.5	**49.0**
Totals	**4.8**	**5.0**	**12.5**	**36.5**	**58.8**

Submillimeter Technology Needs

Critical FY 93 Issues

- Optics technology -- close-out of telescope technology in March with loss of PSR Test-bed facility and technology team
  - Continue panel development
  - Phase 1 test-bed
  - Controls study
- Sensors technology -- loss of leveraged SDIO sponsorship of SIS heterodyne receiver technology leading to loss of key receiver technologists
  - Expand SIS receiver technology

Submillimeter Technology Plan
FY 93

$M	FY 93
OACT Needs	
Optics Technology	
Panel Development	0.50
Phase 1 Test-Bed	0.10
Controls Study	0.10
Sensors Technology	
SIS Heterodyne Receivers Augmentation*	0.30
Total	**1.00**
Astrophysics Plan	
Definition	0.18
Technology	0.00
Total	**0.18**

*=Current funding at $3.0M

Plan for FY 94 and outyears will be worked over the next few months by the ATPAT

AIM Technology Needs

Critical FY 93 Issues

- Reduction of Micro-precision CSI to below minimum sustaining levels for interferometer technology
- POINTS-specific technology delayed and additional workforce and scope reductions required in FY 93
- Suspension of OSI study activities in July with loss of mission/systems engineering and metrology development continuity into FY 94

AIM Technology Plan
FY 93

$M	FY 93
OACT Needs	
Technology	
Micro-Precision CSI Augmentation*	0.90
Fine Pointing	0.20
Metrology	0.25
Technology Definition	0.15
Total	**1.50**
Astrophysics Plan	
Definition	0.18
Technology	0.00
Total	**0.18**

*=Current funding at $0.6M

Plan for FY 94 and outyears will be worked over the next few months by the ATPAT

Summary of Critical FY 93 Needs

$M	OACT	Astrophysics	Total
SOFIA	6.85	1.90	8.75
SIRTF	6.20	8.00	14.20
Explorers - FUSE*	1.00	4.80	5.80
Submillimeter*	4.00	0.18	4.18
AIM*	2.10	0.18	2.28
Total	20.15	15.06	35.21

OACT figures include current $4.57M investment ($3.0 M in submillimeter heterodyne receivers, $0.97M for IR direct detectors and $0.6M for interferometer technology)

*=Non-ATD investments

I.A AstroTech 21 History

AstroTech 21 is the outgrowth of a study begun in 1984 by the Space Science Board (SSB) at NASA's request, to determine the principal issues that space science would face in the period between 1995 and 2015. The SSB's 1988 report recommended four programmatic avenues:

- Imaging interferometers;
- Large-aperture telescopes and improved spectrometers;
- A Laser Gravitational Wave Observatory in Space (LAGOS);
- A small-satellite program responsive to opportunities at all wavelengths.

During early 1989, NASA's Astrophysics Division began to define a New Century Astronomy Program which would implement the SSB's recommendations. Substantial funding would be required to develop the new technologies for this program. The AstroTech 21 Program was conceived as the mechanism for identifying those technologies and bringing them to a state of readiness. In addition, the recommendations of a National Academy of Sciences survey of the astronomical science in the 1990s, published in 1991 under the title *The Decade of Discovery in Astronomy and Astrophysics* (often referred to as the "Bahcall Report"), have been incorporated into the AstroTech 21 program. The Jet Propulsion Laboratory (JPL) assisted NASA in defining AstroTech 21 through a series of workshops and recording their work in workshop proceedings.

Implementation of the AstroTech 21 plan is to be jointly supported by the Astrophysics Division and the Office of Advanced Concepts and Technology (OACT, formerly the Office of Aeronautics and Space Technology). OACT is to provide most of the resources for technology development , while mission concept and definition studies (during pre-Phase A, Phase A, and Phase B) are being carried out under the management of the Advanced Programs Branch of the Astrophysics Division. The mission concept and definition studies will determine and refine, through an iterative process, mission advanced technology requirements. When the agreed-upon levels of technological maturity have been reached, the Astrophysics Division will assume principal responsibility for advanced technology development and infusion into the project's detailed design and development phase, Phase C/D.

The AstroTech 21 program is being carried out in several phases:

- Ten workshops have been convened, and one more, a Spacecraft Systems Technology Workshop, is planned for Spring 1993. Each workshop brought together scientists, engineers, NASA planners and managers, and industry representatives, to formulate the Astrophysics Division advanced technology development strategy. The general format for each workshop began with presentations and discussions in plenary sessions, followed by individual discipline-specific panel discussions, where detailed recommendations for technology development were drawn up. Ultimately, recommendations were discussed and ranked in a plenary session, in a process analogous to a peer review. The recommendations were presented to NASA in the form of workshop proceedings, produced in general by JPL (see Workshop schedule and Bibliography below).

- The AstroTech 21 Workshops looked at the planning and design of future Astrophysics missions in three stages:
  - Science objectives and architectures for achieving them
  - Technology requirements for specific mission concepts
  - Integration of technology and mission concepts and opportunities.

- Five key areas of development were considered:
  - Sensors
  - Optics
  - Interferometry
  - Spacecraft
  - Mission Operations and Information.

- Based on these workshops, Technology Plans were developed for specific missions. These documents are iterated with study or project managers and scientists, and are often reviewed by discipline Management Operations Working Groups (MOWGs) or Science Working Groups (SWGs), with members from universities, NASA field centers, other national laboratories, and industry.

- The purpose of the Plans is to present detailed statements of Astrophysics mission technology development needs to OACT, including the current state-of-the-art, mission requirements, readiness dates, criticality and urgency of each technology, as well as development schedules and funding profiles. To date, four of these Mission Technology Plans have been produced, for

- •• Stratospheric Observatory For Infrared Astronomy (SOFIA)
- •• Space Infrared Telescope Facility (SIRTF)
- •• Submillimeter Intermediate Mission/Far Infrared Space Telescope (SMIM/FIRST)
- •• Astrometric Interferometry Mission (AIM).

AstroTech 21 Workshop schedule, ordered by series and volume number of the Proceedings:

* High-Energy Astrophysics in the 21st Century (Taos, NM, 11-14 December 1989). Note, the proceedings of this workshop were published by the American Institute of Physics prior to the adoption of numbering system of the following proceedings.

I.1 *Science Objectives and Architectures for Optical Interferometry in Space* (Pasadena, CA, 12-13 March 1990)

I.2 *Science Objectives and Architectures for Submillimeter Interferometry in Space* (Columbia, MD, 10-11 December 1990)

II.1 *Technologies for Optical Interferometry in Space* (Pasadena, CA, 30 April-1 May 1990)

II.2 *Technologies for a Laser Gravitational Wave Observatory in Space* (Annapolis, MD, April 1990)

II.3 *Technologies for Advanced Very Long Baseline Interferometry in Space* (Columbia, MD, 12-13 February 1991)

II.4 *Technologies for Large Filled-Aperture Telescopes in Space* (Pasadena, CA, 4-5 March 1991)

III.1 *Information Systems for Space Astrophysics in the 21st Century* (Annapolis, MD, 23-25 May 1990)

III.2 *Sensor Systems for Space Astrophysics in the 21st Century* (Pasadena, CA, 23-25 January 1991)

III.3 *Optics Systems Technology for Astrophysics in the 21st Century* (Pasadena, CA, 6-8 March 1991)

III.4 *Spacecraft Systems Technology for Astrophysics in the 21st Century*, (workshop planned, Columbia, MD, Spring '93)

I.B "Win-Win" Management Strategy

We believe that the implementation of AstroTech 21 will constitute a classic "win-win" situation:

- The Astrophysics community wins because OACT's implementation of AstroTech 21 will greatly increase technology development activities that are critical to that community's future needs.

- OACT wins because (1) its AstroTech 21 implementation activities support one of NASA's principal goals -- advancing Space Science; (2) the technology is useful and readily transferable; and (3) the science community will become an advocate of OACT programs.

- NASA's stakeholders -- the U.S. taxpayers -- win because (1) Astrophysics flight programs will be implemented faster, at lower cost, and with better results; and (2) AstroTech 21 contributes to the U.S. technological base.

To implement this "win-win" strategy, we developed a new management paradigm for the AstroTech 21 program. This paradigm centers around the establishment of a Study/Project Technologist. This individual will:

- Manage the implementation of the technology development at the working level, report to the Study/Project Manager, and, thus, be located at the project development center.

- Encourage the use of extra-center talent and expertise, especially those seeking to maximize the involvement of universities and small entrepreneurial firms. The objective is to better utilize NASA's technology development resources to truly fuel the "technological engine of America."

- Provide a "positive stress on the system" by creating a mechanism internal to the study/project office with the explicit goal of technology infusion.

In addition, the Study/Project Technologist will ensure that the technology development is properly focused, technically sound, cutting-edge, and meets the project's system engineering and integration requirements. Finally, the Study/Project Technologist will report on a periodic basis to the Astrophysics-Technology Team (ATT), jointly created by Codes SZ and C, on the progress that has been made in each technology development area as well as on new opportunities for technology infusion.

I.C Technology Transfer

Each new astrophysics mission usually requires at least an order of magnitude improvement in some measure of instrument performance. Because the astrophysical science goals continually push the envelope of technology, future generations of space astrophysics missions require that technology be pushed well beyond the current state of the art. The central goal of AstroTech 21 is to assure that this takes place in a planned, systematic, and efficient way.

Much of the technology of the AstroTech 21 program is "dual use" technology. It addresses not only the needs of the Space Astrophysics program, but it also contributes to the technological base of the U.S. This is illustrated in the following matrix that relates the *using* and *driving* technologies of AIM, SIRTF, SMIM/FIRST, and SOFIA to twelve "Emerging Technologies":

Department of Commerce Emerging Technologies	**Astrophysics Mission**			
	AIM	**SIRTF**	**SMIM**	**SOFIA**
Advanced Materials	Driving		Using	Driving
Superconductors		Using		
Advanced Semiconductor Devices	Using	Using	Using	
Digital Imaging Technology				Using
High-Density Data Storage	Using		Using	
High-Performance Computing	Using			
Optoelectronics	Driving			Using
Artificial Intelligence				
Flexible Computer-Integrated Mfg	Driving	Driving		Driving
Sensor Technology	Driving	Driving	Driving	Driving
Biotechnology				
Medical Devices and Diagnosis				

Key: Driving Technology
Using Technology

These emerging technologies have been identified by the Department of Commerce as having the potential to create a multitude of new products and services and to substantially advance national productivity and quality by the year 2000.

More detailed descriptions of the transfer potentials of the technologies are given in the technology plans included in Sections II, III, and IV.

I.D Organization of the Plan

The Plan is organized in two volumes according two complementary perspectives:

- Missions, and

- Integrated Technologies.

The first of these volumes focuses on specific missions and flight programs. This volume consists of four sections:

- Section II -- Technologies of missions and programs that offer *continuous flight opportunities* over a considerable stretch of time, such as SOFIA and the Explorer Program;

- Section III -- Technologies for *near- to mid-term missions and programs*, which are expected to initiate development in the approximate time frame from 1995 to 2000, such as SIRTF; and

- Section IV -- Technologies for *long-term missions and programs*, which are not likely to begin development until the next century.

- Section V -- AstroTech 21 test-beds.

The stage of concept definition of the technologies of volume 1 ranges from pre-phase A, as for example the technologies of AIM (see section III.C), to phase B, as for example the technologies of SOFIA.

The second volume of the plan, which comprises sections VI, VII, and VIII, deals with technology disciplines, such as Optics and Spacecraft Technology. The latter two sections contain acronyms and a glossary, and the bibliography.

Many of the topics of volume two are also present in volume one; but here, in volume two, they are organized along technological lines. In addition, the specific technologies described in volume two have been recognized as likely to be critical for future Astrophysics missions and flight programs; but they are, at present, in a relatively immature stage of concept definition and development. Many of them are generic in nature and have no affiliation yet with a specific mission or flight program. However, as the Astrophysics mission and flight program plans evolve, and new needs arise, and as these generic technologies get better defined, many of them are expected to find application in specific missions and flight programs. They will then transition from volume two to volume one of the AstroTech 21 plan.

Finally, AstroTech 21 is an evolving program. As space Astrophysics evolves, so do its plans for future missions, its technology needs, and, hence, AstroTech 21. Mature technologies will transition out of the program into phase C/D development, but new ones will be added. As this happens, the content of this document changes. Pages will be removed, while others will be added. The new pages may come from many sources -- scientists and engineers at universities, in industry, at national laboratories, and NASA Headquarters. No attempt will be made to maintain a uniform style or format. This is a living document for working engineers, scientists, and managers.

TECHNOLOGY PLAN

FOR THE

STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY (SOFIA)

March 19, 1993

To be submitted to Gregory Reck

Associate Administrator
Office of Advanced Concepts and Technology
NASA Headquarters

Michael S. Kaplan
Acting Chief, Advanced Programs Branch
Astrophysics Division

SOFIA

Program Manager:	Mike Kaplan, NASA HQs
Program Scientist:	Larry Caroff, NASA HQs
Project Manager:	Chris Wiltsee, ARC
Project Technologist:	Ramsey Melugin, ARC
Project Scientist:	Ed Erickson, ARC

3/19/93

TABLE OF CONTENTS

RATIONALE

[Mike Kaplan will write this.]

I. INTRODUCTION

The purpose of this plan is to describe to the Office of Advanced Concepts and Technology the critical technology needs of the Stratospheric Observatory for Infrared Astronomy (SOFIA).

SOFIA is a planned 2.5-m aperture Cassegrain telescope, with a primary mirror f-ratio near 1.4, that is to be installed in a Boeing 747 aircraft and operated at altitudes from 41,000 to 46,000 feet. It is a follow-up mission to NASA's Kuiper Airborne Observatory (KAO), which consists of a 0.9 m telescope in a Lockheed C-141 jet transport and has served the astronomical research community since 1974. SOFIA's sensitivity will be nearly ten times that of KAO, while its angular resolution will be three times greater.

SOFIA's capabilities are optimized for infrared and submillimeter observations, though its full wavelength range extends from 0.3 μm to 1600 μm. Much of SOFIA's spectral range is either inaccessible from the ground (fig. 1) or can be detected only from space at much greater expense.

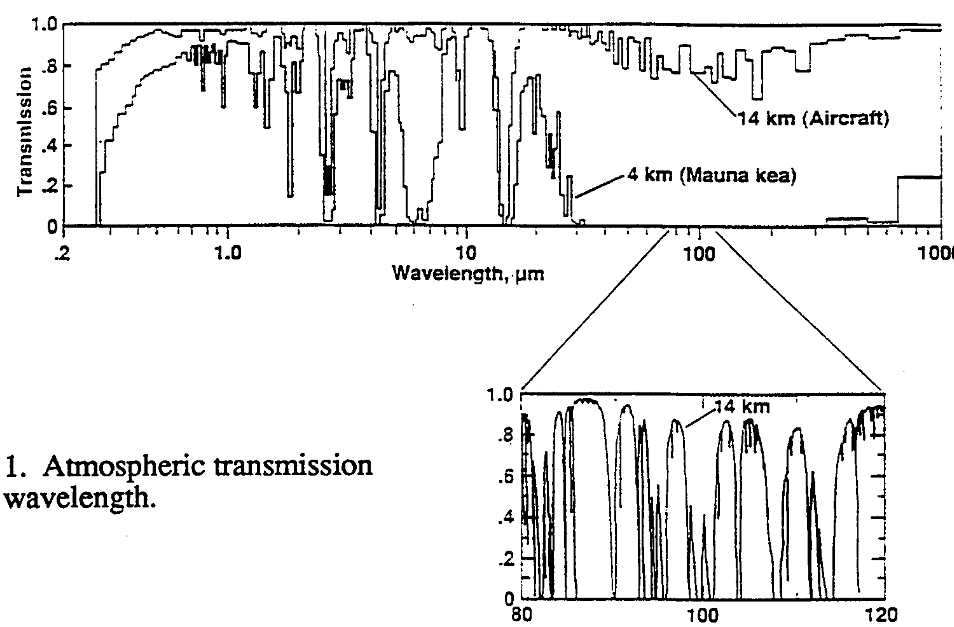


Figure 1. Atmospheric transmission versus wavelength.

SOFIA's science objectives will focus on star and planet formation, the dynamics and chemistry of the interstellar medium, galactic structure and evolution, and the sun and other solar system bodies. It will thus complement the capabilities of other NASA missions, such as HST and SIRTF, and the archived data sets of the KAO, IRAS, and COBE. In addition, SOFIA will offer hands-on training for graduate students and postdocs, and the testing of new instrumentation. Approximately 160 research flights are envisioned per year over an estimated lifetime of 20 years (table 1).

- Wavelength: 0.3 - 1600 μm
- Aperture: 2.5 m
- Angular resolution:
  - 1 - 3 arc-sec, $\lambda < 15$ μm
  - (λ/10 μm) arc-sec, $\lambda > 15$ μm
- Deployable for all-sky coverage
- 160 8-hour flights per year
- 20-year lifetime
- Routine access to infrared spectral region
- Rapid response:
  - Annual peer review
  - Ephemeral events
  - State-of-the-art instruments
- Community participation
  - ≈ 15 instruments yearly
  - ≈ 50 P.I. teams yearly
  - Hands-on training for graduate students and postdocs

Table 1. SOFIA characteristics.

SOFIA will be able to observe from anywhere on earth, which is important for certain transient events, such as eclipses and occultations. Furthermore, this mobility will allow SOFIA to serve as a goodwill ambassador for NASA throughout the U.S. and the rest of the world, and stimulate interest in astronomy and NASA missions among the public and students at all levels.

In 1991, the Astronomy and Astrophysics Survey Committee of the National Research Council recommended SOFIA as the top priority new mission in the Moderate Program category. The Committee stated that "SOFIA provides the highest-resolution spectroscopy of any planned facility for wavelengths between 30 and 300 microns, and its large aperture will yield high-spatial-resolution observations that will complement SIRTF's capabilities. ... SOFIA represents the natural evolutionary replacement for the KAO."[1]

1 Astronomy and Astrophysics Survey Committee. *The Decade of Discovery in Astronomy and Astrophysics.* Washington, DC: National Academy Press. 1991. Page 23.

II. ORGANIZATION OF THE PLAN

Section III of this plan reviews the chief technology challenges posed by the SOFIA project. Of these challenges, three are identified as presenting significant risks to the project's development and, hence, are critical. They require early development and demonstration so that Phase C/D can begin without any of SOFIA's technologies remaining on the critical path.

Section IV describes SOFIA's three critical technology challenges. The focus is on the factors that make the technologies critical, their current status of development, and the specific capabilities that still need to be developed and demonstrated to move them off the critical path. These discussions are followed by major milestones and funding schedules.

Section V discusses SOFIA's technology transfer potential. Section VI summarizes the major milestones and funding schedule of the overall SOFIA technology development effort.

III. TECHNOLOGY CHALLENGES

Modifying a Boeing 747 aircraft to house a 2.5 m aperture telescope (note, the primary mirror's actual physical diameter will be approximately 2.7 m) in a cavity that during observations is open to the environment at an altitude of 40,000-plus feet, yet offers the attending scientists hands-on access to their instruments under pressurized conditions, constitutes a major engineering undertaking. According to present plans, the cavity will be located in the aft section of the aircraft. It needs to be of sufficient size to house the optics of the approximately 36,000-pound telescope assembly; and the opening must allow the telescope to point between elevation angles of 20 and 60 degrees unvignetted (figures 2, 3).

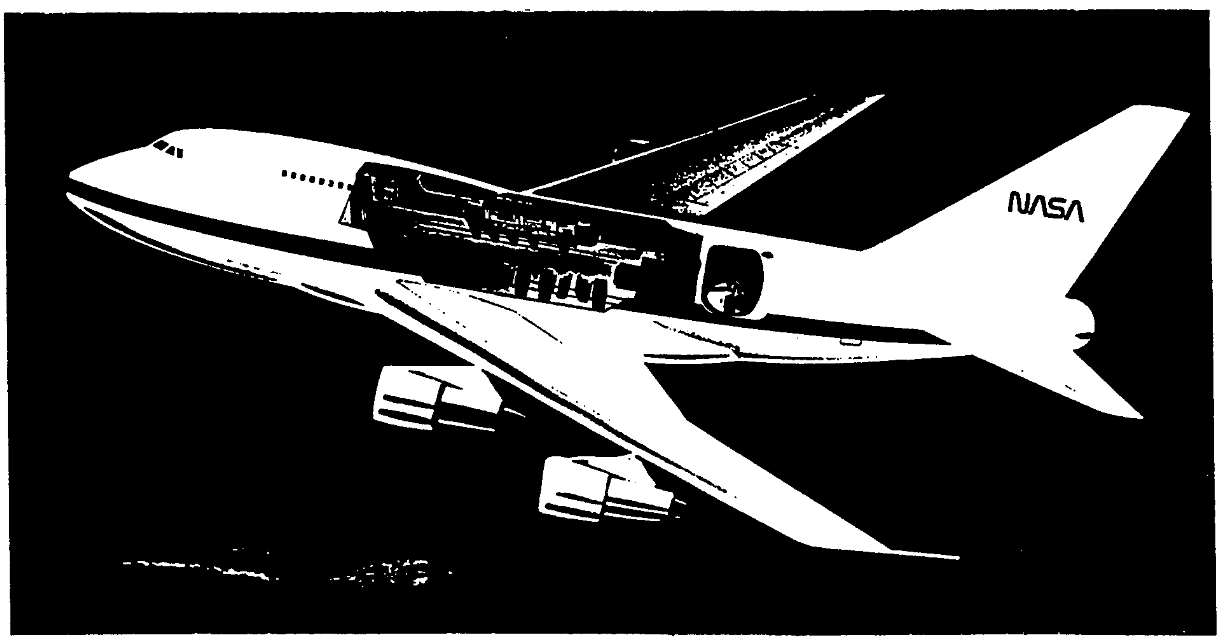


Figure 2. Model of the Boeing 747 SOFIA aircraft, showing telescope and observatory control cabin.

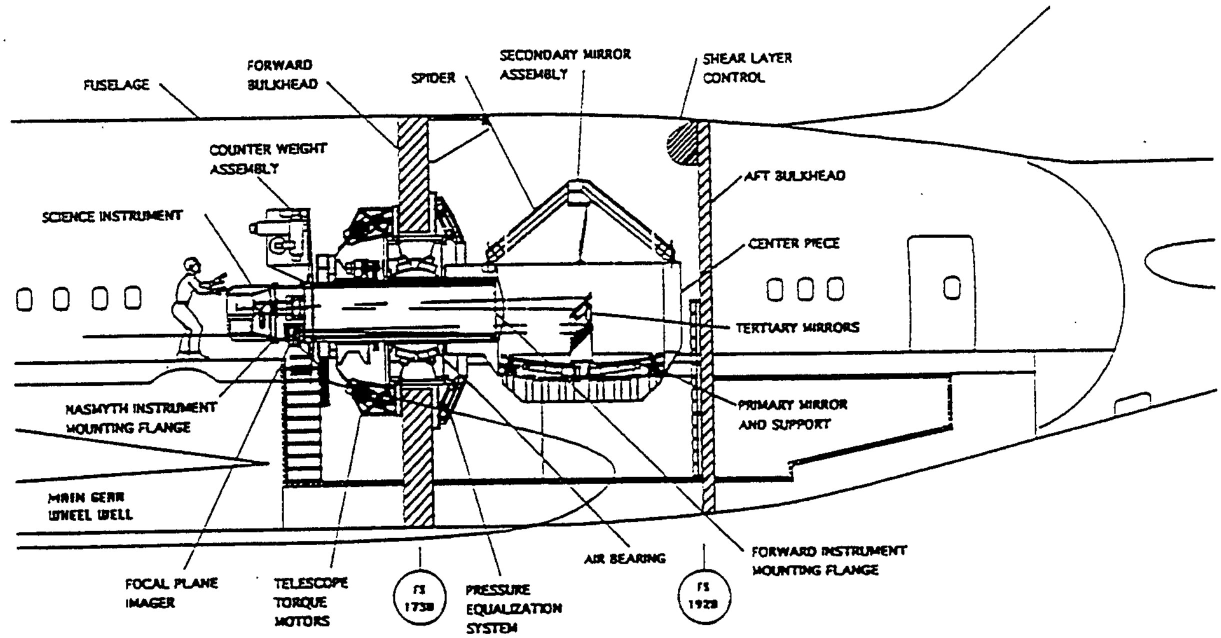


Figure 3. SOFIA telescope installed in Boeing 747.

The chief technology challenges in modifying the aircraft and constructing the observatory are the following:

- Constructing the cavity bulkheads and reinforcing the fuselage frame to accommodate the cavity, cavity opening, and telescope assembly, yet maintaining the aircraft's structural integrity and flight stability. (SOFIA's cavity and cavity opening will be the largest ever built in an aircraft, and the first of any significance on a 747.)

- Constructing the cavity door/moving port mechanism, including aerodynamic shear layer control provisions.

- Re-routing aircraft control cables and other systems that pass through the fuselage section affected by the cavity.

- Developing state-of-the-art telescope operations systems (cavity cooling, tracking hardware and software, torquer motors, secondary mirror chopper mechanism, pointing control subsystems, data acquisition, etc.).

- Isolating and damping the telescope assembly against a broad spectrum of mechanically and acoustically induced vibrations, and stabilizing it against the rolling, pitching, and yawing of the aircraft.

- Controlling the shear layer across the open cavity and minimizing the layer's thickness to ensure a sufficiently stable aero-optic environment for astronomical observations.

- Constructing the 2.7-m physical diameter, f/1.4 primary mirror and mirror mount that meet SOFIA's stringent tolerances of weight and optical quality, while withstanding exposure to the severe temperature and pressure cycles encountered by flying to a cruising altitude of 40,000-plus feet, remaining there for up to 8 hours per research flight, and then returning within approximately 30 minutes to ground environmental conditions.

In order to assess the magnitude of these technology challenges, NASA has carried out several definition studies since 1986, both in-house at the Ames Research Center and through outside contractors in the U.S. and overseas. In addition, the SOFIA project was reviewed in 1989 and 1990 by two NASA Non-Advocacy Review (NAR) panels. The consensus view that emerged from these studies and reviews was that all but three of the SOFIA technology challenges listed above are sufficiently within current technology and engineering know-how to allow Phase C/D development to begin with little risk. The three exceptions are the following:

- Design and development of the shear layer control system for the fuselage open cavity, including demonstration by wind tunnel testing and computational fluid dynamics simulation.

- Design and development of a large spherical air bearing or, alternatively, spherical magnetic bearing for the telescope assembly's virtually frictionless rotational suspension system.

- Design and development of the 2.7 m, f/1.4 extremely light-weight primary mirror and mirror mount assembly.

These three critical technologies were identified by the definition studies and the NAR panels as requiring significant extensions in size, performance, and, in the case of the second and third technologies, the ability to withstand environmental exposures beyond current technological experience and capability. These extensions introduce uncertainties and considerable risks to the development schedule and cost of SOFIA, and they place these leading-edge subsystems on the critical path in the project's overall development. In fact, they raise the possibility that NASA's new paradigm of "Better, Faster, Cheaper" cannot be met unless adequate technology demonstration efforts are carried out prior to Phase C/D development.

For example, if any of the three critical technologies slows down or delays SOFIA construction, the potential costs could be as high as $500,000 per month ((60 persons x $100 K/person/year)/12 month/yr) or $6 M per year during peak Phase C/D development. This would be a significant fraction of the project's expected peak expenditure rate of about $40 M per year.

The SOFIA Program and Project Offices consider these risks in schedule and cost excessive. In their view, the responsible course of action is to remove these three undemonstrated technologies from the critical path by Pre-Phase C/D development efforts. The rest of this document describes the steps required to accomplish this.

IV. CRITICAL TECHNOLOGIES

A. SHEAR LAYER CONTROL AND CAVITY-ACOUSTIC QUIETING

Criticality:

The chief technical problems created by SOFIA's open cavity configuration are aircraft safety, aerodynamic drag, telescope disturbances, and seeing. Wind tunnel tests have shown that violent shear layer oscillations and dangerous levels of acoustic loading occur in cavities with untreated rectangular openings. In addition, seeing is degraded due to fluctuations of the refractive index in the shear layer.

Experience with the KAO and the Airborne Optical Adjunct (AOA, an SDIO aircraft with an open cavity of dimensions comparable to those of the KAO) provides some practical guidance in dealing with these problems, but only to a limited degree. SOFIA will operate at higher speeds and be fitted with a much larger cavity in a very different aircraft configuration. Furthermore, unlike the cavities of the KAO and AOA, which are in front of the wings, that of SOFIA will be installed behind the wings to save cost. However, mounting the telescope in the aft section of the fuselage has the disadvantage of exposing the cavity to a thicker and more turbulent fuselage boundary layer, which in turn may induce higher acoustic loads in the cavity. A thicker shear layer also is expected to have a more severe effect on seeing.

Preliminary analysis suggests that the problems associated with an aft-mounted telescope can be mitigated by fitting a diverter in front of the cavity opening that splits the fuselage boundary layer and deflects it around the cavity. The shear layer flowing across the cavity opening would then be thinner and less energetic, and the acoustic loads induced in the cavity would be weaker. Furthermore, the seeing would be less degraded. However, this thinner shear layer would also be more unstable than a thicker shear layer. This latter instability can probably be controlled by mounting a specially contoured ramp in the aft section of the cavity opening, designed to allow the shear layer to re-attach itself smoothly to the fuselage downstream from the cavity opening.

- To minimize the shear layer oscillations, acoustic loads, and degradation in seeing associated with an aft-mounted cavity, it is critical that the configurations of cavity opening, boundary layer diverter, and ramp be optimized. Particular attention needs to be paid to the shear layer re-attachment problem because of the proximity of empennage control surfaces.

- Solving these problems and determining the flow dynamics within the cavity and across the cavity opening requires three different but complementary approaches:

  - Simulation and analysis through computational fluid dynamics (CFD).

  - Sub-scale prototype wind tunnel (WT) testing.

  - Active cavity-acoustic quieting demonstration.

1. Simulation and Analysis through CFD:

CFD is needed to complement the traditional WT testing for several reasons:

- CFD produces data that are difficult or impossible to obtain through WT testing, such as the integrated force and moment data on cavity, telescope, and aircraft surfaces, torques exerted on the telescope by acoustic fluctuations, and temperature and density data in the shear layer. Shear layer temperature and density, in turn, determine the refractive index and, therefore, are needed for the aero-optics (i.e., seeing) calculations.

- CFD simulations produce data (e.g., flow velocity, pressure, density, temperature) at each of roughly 4-5 million grid points throughout the simulated volume, while WT testing yields measurements at only a few hundred sampling points. Thus, CFD allows much more detailed analysis than WT testing.

  (The many grid points in SOFIA CFD simulations are needed to model realistically the small-scale flow characteristics in the shear layer and near cavity, telescope, and aircraft surfaces, and to capture the physics of high-frequency acoustics.)

- CFD studies are planned to precede wind tunnel tests and will be used in developing the wind tunnel test plan and initial candidate test configurations.

2. Sub-Scale Prototype WT Testing:

WT testing serves two crucial functions:

- It is needed to validate CFD simulations, as discussed in more detail below.

- It is far more efficient in testing different cases than CFD simulations. For example, whereas the CFD simulation of a new design requires up to 800 central processing units (approximately equivalent to hours) on a supercomputer, a WT test of a new design takes on the order of minutes (once the test model is constructed). Running this design then through the full test matrix of Mach numbers (approximately 0.3-0.9), angles of attack (≈ 0-5 degrees), and side-slip angles (≈ 0-4 degrees) takes a few hours. (WT test models will be 1/14 of full scale.)

3. Active Cavity-Acoustic Quieting Demonstration:

The shear layer control system described above is a *passive* system, which probably will not be able to reduce cavity acoustic noise below approximately 130 to 140 dBA. Acoustic loads of this magnitude expose the telescope to significant mechanical disturbances and impact negatively on telescope pointing. Therefore, it is desirable to quiet further the acoustic levels at critical frequncies within the cavity, hopefully to 110 dBA or below.

- This can only be achieved through *active* acoustic quieting technology. This technology is presently in its nascent stage and needs to be considerably improved to have practical application for SOFIA.

Development and Demonstration:

SOFIA CFD simulations are being carried out in-house at the NASA-Ames Numerical Aerodynamics Simulation (NAS) Facility. The WT tests may also be done in house, at the NASA-Ames 14-foot Transonic WT, although other Agency tunnels would also be applicable.

The CFD studies began in 1989 with simulations of simple 2-D cavities, and emphasis on verification of numerical schemes and turbulence functions. In 1990 and 1991, simulations were performed of a sting-mounted Boeing 747-SP geometry without and with a cavity, which was then located in front of the wings (this test model had no tail surfaces). Comparisons with WT data on the same configurations showed good agreement, demonstrating that CFD is a valid and valuable complementary tool to actual WT testing (figures 4, 5). For example, CFD provided essential loads, telescope torque, and seeing data, as described above.

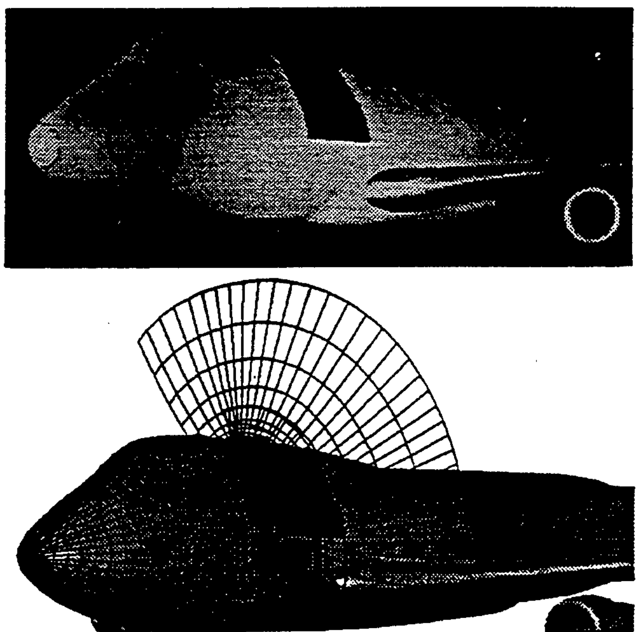


Figure 4. The untreated cavity WT model (top). Some representative CFD grids superimposed on model (bottom).

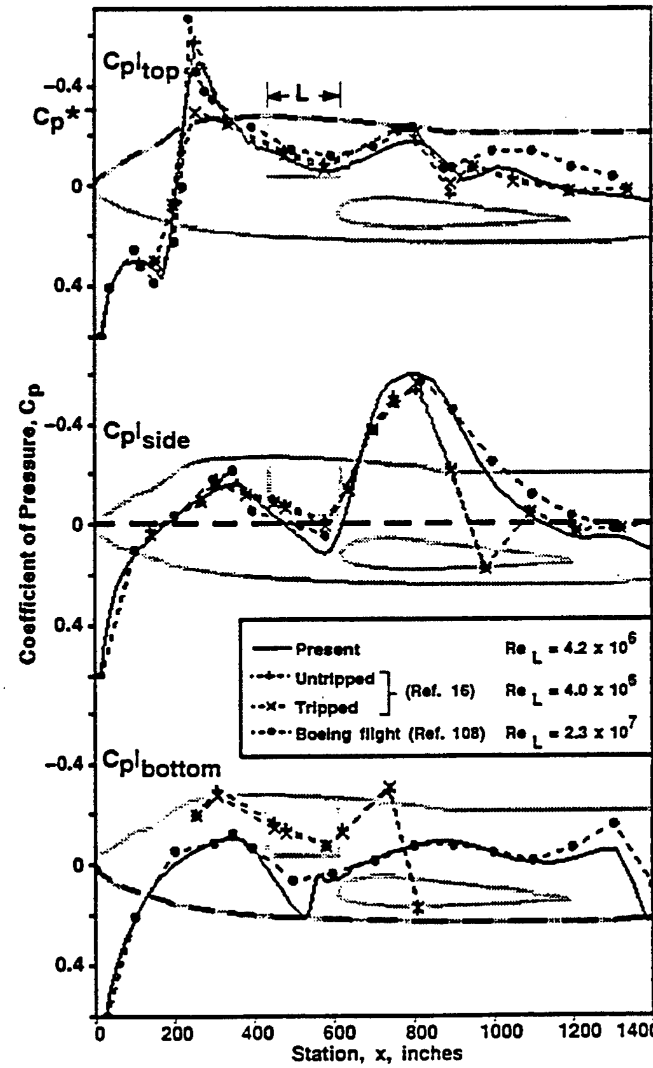


Figure 5. Clean configuration. Pressure coefficient comparison between CFD calculations (solid line), WT results, and Boeing flight results.

At present (February 1993), CFD simulations are being concluded for a clean configuration of a complete Boeing 747-SP aircraft; and coordinate grids for an aft-mounted cavity, several cavity door designs, boundary layer diverters, and aft-mounted shear layer control ramps are planned and, provided that the requested resource augmentation is granted, will be developed. As soon as the clean-configuration is completed, CFD simulations of aircraft plus aft-mounted cavity can begin. The results will be used to select a "best" cavity door, boundary layer diverter, and shear layer control ramp for construction of initial WT models.

After WT testing has begun and while it progresses, CFD simulations for the selected door and diverter models will continue, and the data will be analyzed for loads and cavity environments. CFD and WT results will be compared, and CFD grid geometries and parameters will be adjusted, if necessary, to converge towards the WT results. This process of CFD and WT comparison, and CFD fine-tuning, may go through several iterations, until an acceptable match between CFD and WT results is achieved.

At this point, CFD will be ready to support the design of SOFIA's actual cavity door and shear layer control geometry in the Phase C/D development of the Project.

In addition to the CFD/WT development and demonstration activities just described, both CFD and WT tests are needed for the development and demonstration of active cavity-acoustic quieting technology. CFD and WT tests will initially produce the acoustic power spectral density (PSD) function for the cavity and telescope assembly of the WT test models, using an approach of CFD and WT comparison, and CFD fine-tuning, analogous to the one described above. An example of the in-flight cavity acoustic PSD function determined from the 1991 WT tests of the sting-mounted Boeing 747-SP geometry with cavity, with appropriate scaling to flight and a conservative margin, is shown in fig. 6.

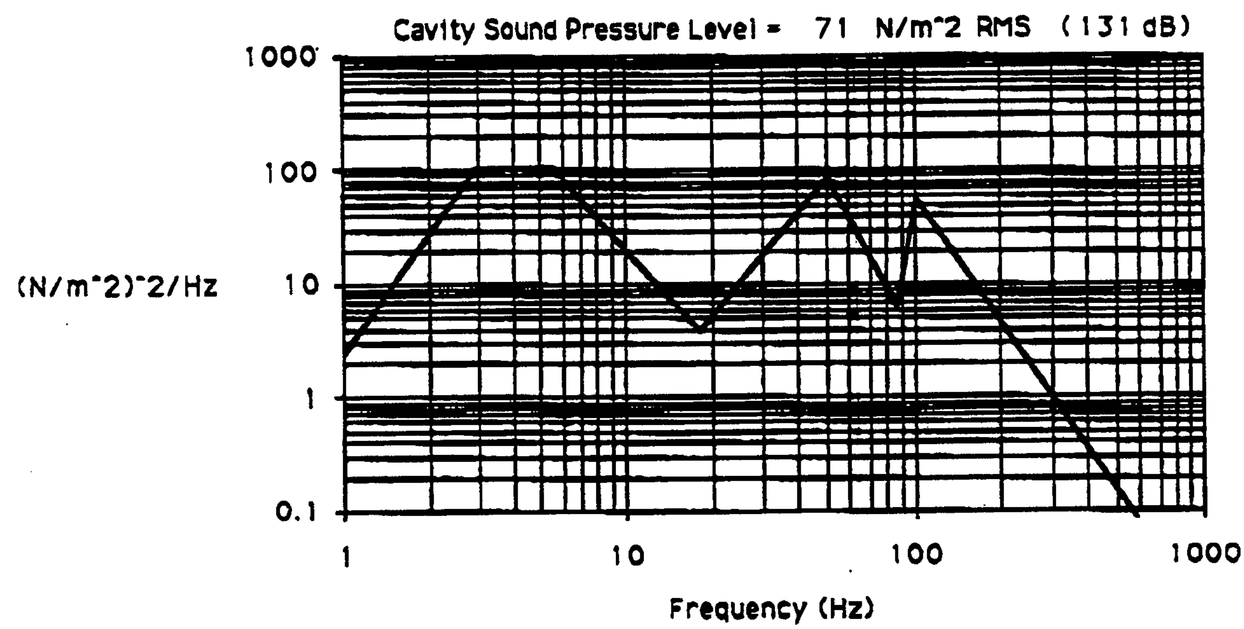


Figure 6. The in-flight cavity-acoustic Power Spectral Density function as determined from 1991 WT tests.

Once the ability of CFD in producing the correct acoustic PSD function for the WT test models and a realistic range of parameters has been demonstrated, the acoustic PSD function will be scaled to the full-scale cavity and telescope assembly, again for a realistic range of parameters (i.e., range of aircraft speeds, flight altitudes, expected temperatures, flight angles, pointing directions of the telescope, and door positions). The results will serve as input for the development and demonstration of the full-scale active cavity-acoustic quieting technology, possibly in concert with NASA's Langley Research Center.

Milestones and Funding Schedule:

CFD is an important precursor to WT testing and needs to be augmented now to speed up the developments just described and increase the rate at which CFD simulations can be carried out and analyzed. Furthermore, the CFD results will be used to support a New Start decision in the summer of 1993. Actual WT tests are expected to start sometime early in 1994 given funding availability (see fig. 7).

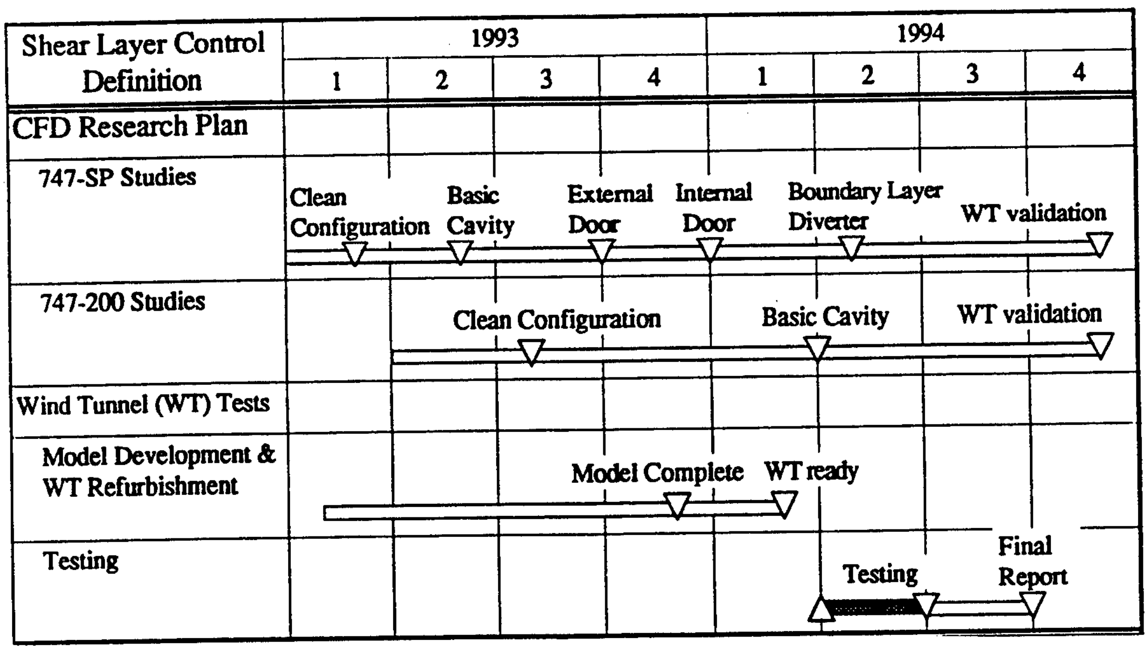


Figure 7. Shear layer control development schedule.

Additional ATD funding of $0.35 M, for a total augmentation of $ 0.5 M in FY 1993, and $1.25 M in FY 1994, would be used to increase the number of CFD researchers from the current 1.5 to approximately 5, and to purchase workstations and some high-density mass storage devices used to archive the large amount of data that will be generated. Basically, each person will support one run, lasting 6-9 months from coding through data analysis.

The additional ATD funding would allow meeting the following CFD milestones:

- Completion of basic cavity configuration by mid-1993.

- Completion of 2-3 door design simulations for the 747-SP and for a possibly alternate Boeing model, the 747-200, by March 1994. A viable shear layer control design will be a key input to WT tests in early 1994.

- Baseline model validation through WT test by late 1994 (based on WT tests performed early in CY 1994).

At this point, a working and validated CFD model of a baseline shear layer control device and cavity door will be available for the development phase (C/D) of the SOFIA project.

WT milestones:

- The Ames 14-foot Transonic WT will undergo de-mothballing and refurbishment from the middle to the end of 1993 or early 1994 (assuming funding), and test planning and training activities will get underway.

- The initial reconfigurable WT test model will be constructed in 7-8 months and the WT staff ready by early 1994.

- The WT tests themselves could take as little as 2-3 months, with a like period of data reduction and data analysis. Should problems be encountered, this period can be extended into the very early part of SOFIA's development phase without too much disruption.

At this point, a shear layer control device will have been WT-proven through a large operating envelope and the development phase (C/D) of the SOFIA project can proceed with greatly reduced risk.

B. DEMONSTRATION OF ROTATIONAL ISOLATION

Criticality:

SOFIA operations require that the telescope remains pointed at an astronomical target to within 0.2 arc-seconds r.m.s.

- Thus, it is critical that the telescope's three rotational degrees of freedom -- 20 to 60 degrees in elevation angle, and ± 4 degrees in cross elevation and about the line of sight -- be nearly perfectly isolated from the motions of the rest of the aircraft.

Current Status:

Rotational isolation will be accomplished via a spherical air bearing or, alternatively, a spherical magnetic bearing. Both types of bearings consist of a central sphere surrounded by a stator, or spherical outer casing sub-assembly, that reacts to the pressure loads. The bearing will be located at the center of mass of the telescope (requiring a counterweight on the cabin side of the structure) and be able to accommodate the telescope's rotating weight of approximately 25,000 pounds. Both types of bearings reduce friction to nearly zero, and they ensure absence of telescope contamination by the non-air lubricants of other types of bearings or isolators. The telescope's gross elevation motion will be actuated by a spur gear, and its fine motion by three electromagnetic spherical-segment torquers, with ranges of ± 4 degrees.

In addition to the requirements just discussed, the bearing needs to be constructed with an approximately 30 inch-diameter hole through its center for the optical path from the telescope's tertiary mirror to the instruments. It must also be able to withstand a differential pressure load of 18 p.s.i. (which includes a safety margin of 100 percent) from the cabin to the cavity side while operating.

(Translational isolation of the telescope assembly, which will be accomplished via pneumatic isolators, is not considered a critical technology and is not discussed here.)

Development and Demonstration:

The most serious technical difficulty in designing and fabricating SOFIA's bearing is accommodating the telescope's considerable weight:

- In the case of a spherical air bearing, experience exists with the KAO bearing. However, the bearing needs to be scaled up from the KAO's 16-inch diameter to sizes of the order of 48 inches. The difficulty arises from the fact that thermal, structural, and machining imperfections of the bearing scale roughly linearly with size, but the air gap between ball and stator increases by much less (from 0.00075 to 0.00096 inches in a typical design). Overcoming these difficulties will require extending the capabilities of existing machine tools and processes, and, possibly, applying advanced materials, such as composites, that possess very low thermal expansion coefficients and great stiffness-to-weight. Other potential solutions include segmenting the stator sub-assembly.

- Added complications in the case of a spherical air bearing are the limited wrap angle imposed by the requirement of a circa 30-inch central hole and the great weight of spherical air bearings (about 15,000 pounds for a 48-inch diameter bearing).

- A spherical magnetic bearing would overcome some of the problems of a spherical air bearing. Its weight would be approximately half as great, and its air gap could be 15 to 20 times larger. However, a spherical magnetic bearing raises concerns about electromagnetic interference with aircraft and science instrument operation, mechanical damage to telescope systems in case of sudden failure, and possible electromagnetic-induced friction.

Thus it is critical that the present difficulties with the spherical bearing concepts be studied further. System-level design and analysis are needed to understand the tradeoffs between the alternatives and to determine the final requirements. Once this is achieved, a competitive contract will be put in place for a full-scale demonstration of the spherical bearing assembly, with precursor sub-scale demonstrations as needed. This will remove this risky component from the critical path.

Milestones and Funding Schedule:

ATD funds for the rotational isolation and support technology program will be used to fund the initial NASA Ames in-house design work, contractor's design activity, fabrication and test of the demonstration bearing, and the in-house interface control and continued system-level design support during the latter phase of this technology program.

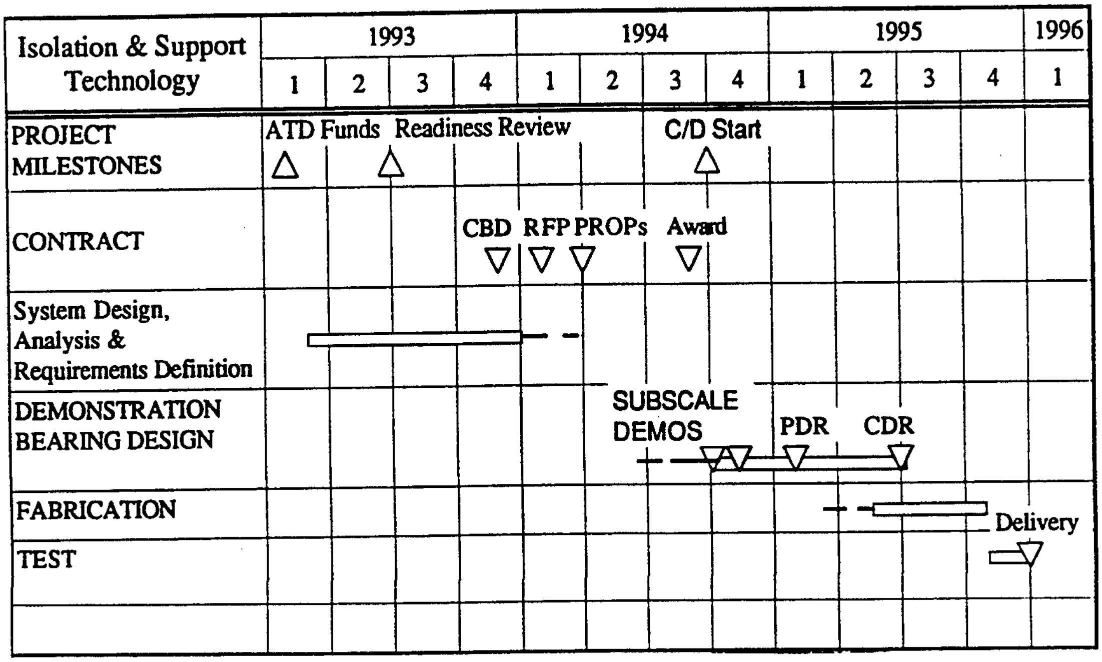


Figure 8. Demonstration rotational isolation development schedule.

ATD funding would allow meeting the following milestones:

- Top level SOFIA telescope system design, spherical bearing requirements definition, and concept tradeoff analyses will be completed by end of 1993.
- Contractor award will initiate the design phase near the end of FY 1994.
- Long-lead fabrications will start early in 1995; all fabrications will be in progress by mid-1995.
- The hardware will be delivered by end of 1995.

C. DEMONSTRATION OF PRIMARY MIRROR ASSEMBLY

Criticality:

The weight of the primary mirror is a significant driver in the SOFIA project. In addition to its own weight contribution, the weight of the primary mirror affects the mirror mount, optical assembly, optical assembly counter weight, torquer motors, vibration isolation system, telescope assembly rotational suspension system, aircraft weight distribution (which may require counter ballast), and aircraft structural modifications. In addition, the primary mirror's weight affects slew time and, hence, the time delay between successive astronomical observations.

Furthermore, the weight of the primary mirror exercises great leverage on the overall cost of the telescope for several reasons. As already stated, the mirror weight geometrically impacts

on the overall telescope weight; and, hence, cost is reduced significantly by lightening the mirror.
However, as explained in more detail below, reducing the mirror's weight reduces its stiffness, which may then need to be provided by an active, moment-compensating rather than passive mirror mount. Active mirror mounts are complex, expensive, and, in SOFIA's application, undemonstrated. Reducing the mirror's weight and, hence, telescope weight also impacts on the mirror materials that can be used, and the mirror's structural design, manufacturing, and polishing methods, all of which become progressively more difficult and uncertain as the mirror's weight is reduced.

Thus, it is critical to demonstrate that

- an ultra light-weight primary mirror and mirror mount can be built, yet ensure that mirror aperture, stiffness, thermal properties, and optical quality meet SOFIA's mission requirements; and

- the cost of the primary mirror/mount assembly remains within an acceptable cost range.

Furthermore, it needs to be recognized that

- determination of the actual achievable primary mirror/mount assembly weight is critical to proceeding with the overall SOFIA system design.

Current Status:

Identifying candidate primary mirror technologies begins with determining acceptable primary mirror aperture and weight ranges (fig. 9). The lower boundary of a usable aperture is set by science requirements and is 2.5 m. The upper boundary is about 3.0 m, and is dictated by engineering constraints of aircraft modification. The upper limit on weight is near 1,800 pounds for the primary mirror/mount assembly, and follows from the leveraged impact of this weight on the overall SOFIA cost and design. However, much would be gained if the actual primary mirror/mount assembly turned out to be 1,200 pounds or even less, and it is imperative to attempt to achieve this for the reasons discussed above. No lower limit on weight has been determined, but physically it is governed by mirror stiffness.

Several existing light-weight mirror construction technologies have been identified that meet SOFIA's requirements of aperture, stiffness, thermal properties, and optical quality. But they do not meet the requirement of weight. For example, the Hubble Space Telescope (HST) mirror, which at the time of its fabrication, in the early 1980s, was considered state-of-the-art with regard to weight and other properties, has an areal density of 184 kg/m^2. In contrast, the aperture/weight ranges for SOFIA discussed above require values in the range from 30 to 60 kg/m^2 and, possibly, even lower. (In comparison, typical ground-based mirrors of the size of the SOFIA primary mirror or greater have areal densities of 250 kg/m^2 or above.)

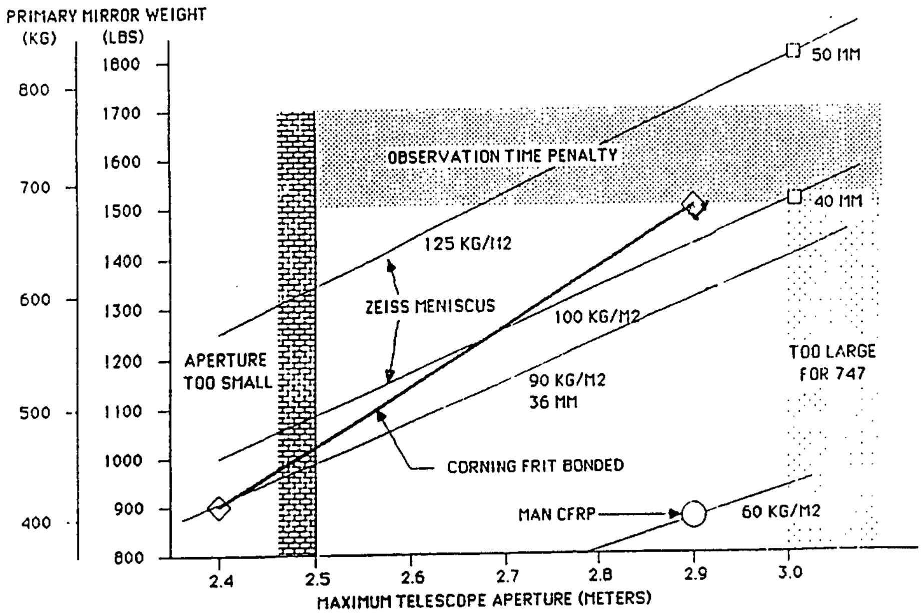


Figure 9. SOFIA primary mirror size/weight trade-off excluding mount.

Development and Demonstration:

Estimates prepared by Eastman Kodak, Hughes Danbury Optical Systems, Corning, Zeiss, Schott, and MAN suggest that current technologies may permit construction of mirrors with areal densities between about 20 and 125 kg/m^2 (table 2). These technologies include frit-bonded, structured-form fused-silica blanks, constant-thickness menisci made of ultra low-expansion fused silica or glassy-ceramic Schott Zerodur, carbon-fiber-reinforced plastic, silicon carbide, and composite/glass integrated mirror blanks. They also include a number of different structural designs and structure manufacture, such as water-jet cutting of monolithic mirror blanks. However, no demonstration mirror of or close to the required aperture has actually been built in the low end of this density range; and tests of sub-scale mirrors with extremely low areal densities indicate that they do not meet the requirements of stiffness and optical quality.

The requirement of stiffness can probably be met through the development of suitable mirror mounts, and suggestions of candidate mounts have been presented to the Project Office by several engineering firms. Preliminary Ames in-house feasibility studies show that gravity induced mirror distortions can be kept within desired r.m.s. surface errors (approximately 1/4 of the He-Ne wavelength at 0.633 μm) by a mounting system such as the passive system proposed by the Steward Observatory Mirror Lab consisting of 44 axial supports and 12 lateral supports (fig. 10). However other mounting systems, passive or active, with different numbers of supports may be feasible as well. No actual demonstration has yet been carried out.

Figure1. Lightweight Primary Mirror Blank Technology for SOFIA

Mean Areal Density (kg/m2)	Applica.	Type	Dia. (m)	Material	F/Ratio
Accomplished:					
252	Lennon[1]	spin-cast	1.8	Ohara E6	1.0
197	ARC[2]	spin-cast	3.5	Ohara E6	1.75
197	WIYN[3]	spin-cast	3.5	Ohara E6	1.75
197	Phillips Lab[4]	spin-cast	3.5	Ohara E6	1.5
184	HST	fused	2.4	ULE	2.3
32	Devel.	frit	1.5	ULE	?
23	Devel.	frit	0.5	fused silica	2.0
Studied:					
217	SOFIA[5]	cast	2.7	Ohara E6	1.6
152	SOFIA[6]	meniscus	2.8	Zerodur	1.2
107	SOFIA[7]	frit	2.5	ULE	1.5
67	SOFIA[8]	frit	2.7	ULE	1.4
60	SOFIA[9]	composite	2.9	CFRP	1.0

1. Lennon Telescope (Vatican)
2. ARC = Astrophysical Research Corp. (U. Chicago, Princeton U., U. Washington, U. New Mexico).
3. WIYN = Wisconsin/Yale/Indiana
4. USAF
5. Kaman/Steward/MAN Study
6. Zeiss/Dornier/MAN Study, constant thickness = 60 mm.
7. HAC/HDOS Study
8. Lockheed/Kodak/Contraves Study
9. MAN Study

Table 2. Light-weight primary mirror blank technology for SOFIA.

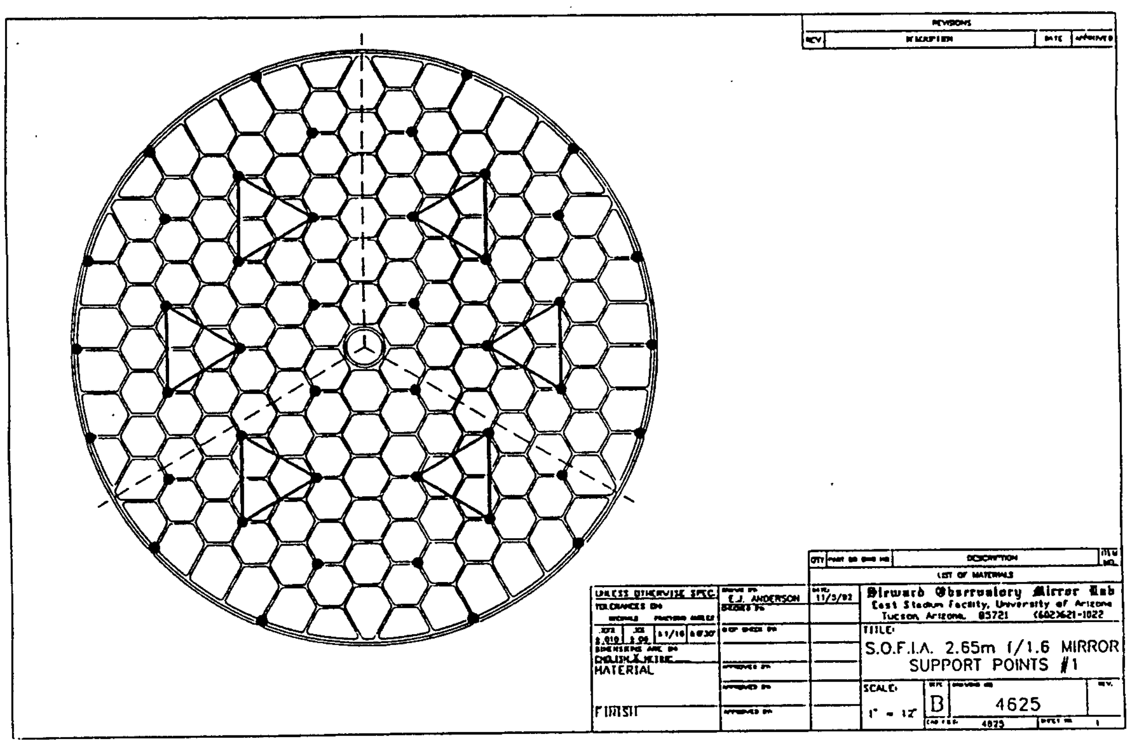


Figure 10. Mirror support points proposed by the Steward Observatory Mirror Lab for a 2.65-m f/1.6 primary mirror.

The great stiffness and extremely low weight which are highly desirable in SOFIA's primary mirror, and the trade-offs that need to be made have not yet been fully discussed. For example, in order to meet its science goals, SOFIA must possess a pointing stability of 0.2 arc-seconds r.m.s. This can only be achieved through great stiffness in the optical system and the overall telescope "dumbbell" structure (i.e., a first natural frequency of the telescope of greater than about 60 Hz). This, in turn, demands extremely low weight in the primary mirror, which has the largest leverage on the weight requirement. If the primary exceeds the best current state-of-the-art areal densities of about 20-60 kg/m^2 (which has not yet been demonstrated for the size of the SOFIA primary and its unique application), the telescope weight budget cannot be achieved while still meeting the stiffness requirement. The only potential solution for this problem would be through extremely sophisticated and as of yet undemonstrated pointing control technologies. Note that achieving SOFIA's required pointing stability by image motion compensation (i.e., moving the secondary or, possibly, additional optical components) is not a viable concept because dynamic IR backgrounds need to be minimized to meet science requirements.

Achieving the primary's required optical quality depends largely on refining current polishing techniques to produce an f-ratio near 1.4. Mirror polishing at f-ratios even faster than 1.4 has been successfully attained, but not at the aperture size and low areal density required. Again, several candidate technology concepts have been suggested, and some promising sub-scale demonstrations have been carried out. Examples are the use of different tool sizes, polishing pressures, and non-contact polishing techniques. But to date, none of the technologies has been demonstrated at full-scale. The Project Office judges that computer-control, or other advanced technologies such as ion figuring, will make the polishing of an f/1.4 primary feasible.

Milestones and Funding Schedule:

ATD funds are needed to demonstrate at full scale the technology capability of constructing SOFIA's primary mirror/mount assembly, including meeting the requirements of stiffness, thermal properties, optical quality, and weight. Only through such a full-scale demonstration can all of these capabilities be demonstrated and, thereby, this difficult, high-technology assembly be removed from the critical path, allowing the rest of the SOFIA project to proceed into phase C/D development at acceptable risk and minimum cost.

The RFP will be released early in 1993, requesting proposals for a primary mirror/mount technology development program that includes multiple, parallel-path sub-scale technology demonstrations where appropriate. Contract awards will be made about 6 months after release of the RFP.

During the initial phase of this program, consideration will be given to the development of technologies ranging from traditional approaches, requiring only minor extensions beyond current technical capabilities, to potentially radically new approaches for solving the engineering and technical challenges of the primary mirror/mount assembly, as described above. In the late 1994 time frame, the most promising technology(s) will be carried forward to full-scale demonstration. During this stage, the final sub-scale demonstration will be made for the selected approach(es).

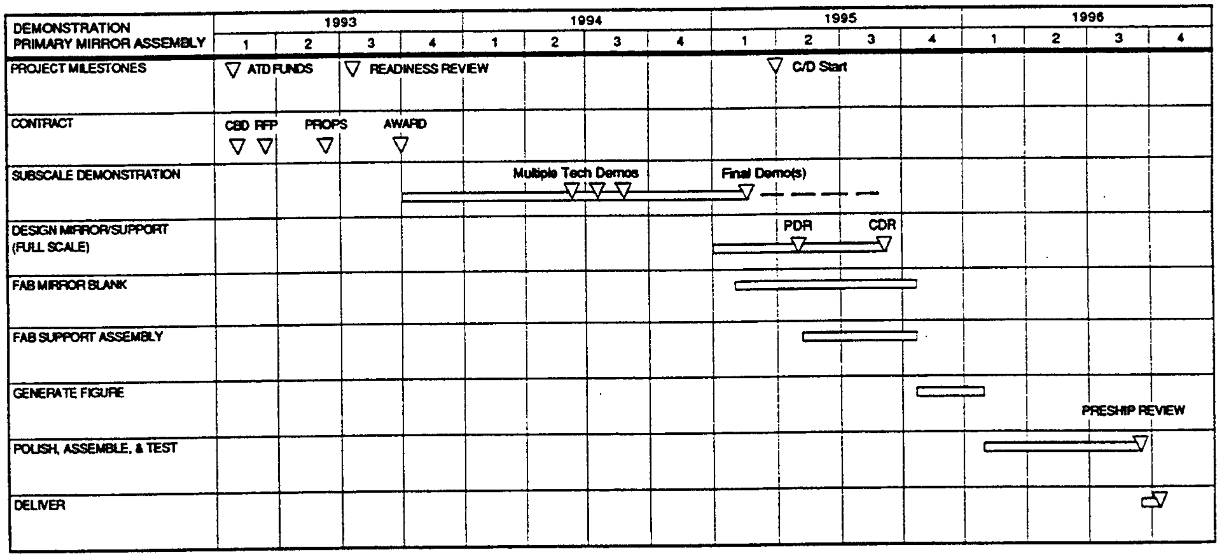


Figure 11. Demonstration primary mirror assembly development schedule.

One possible approach to the final sub-scale technology demonstration might include a two-step scenario as follows:

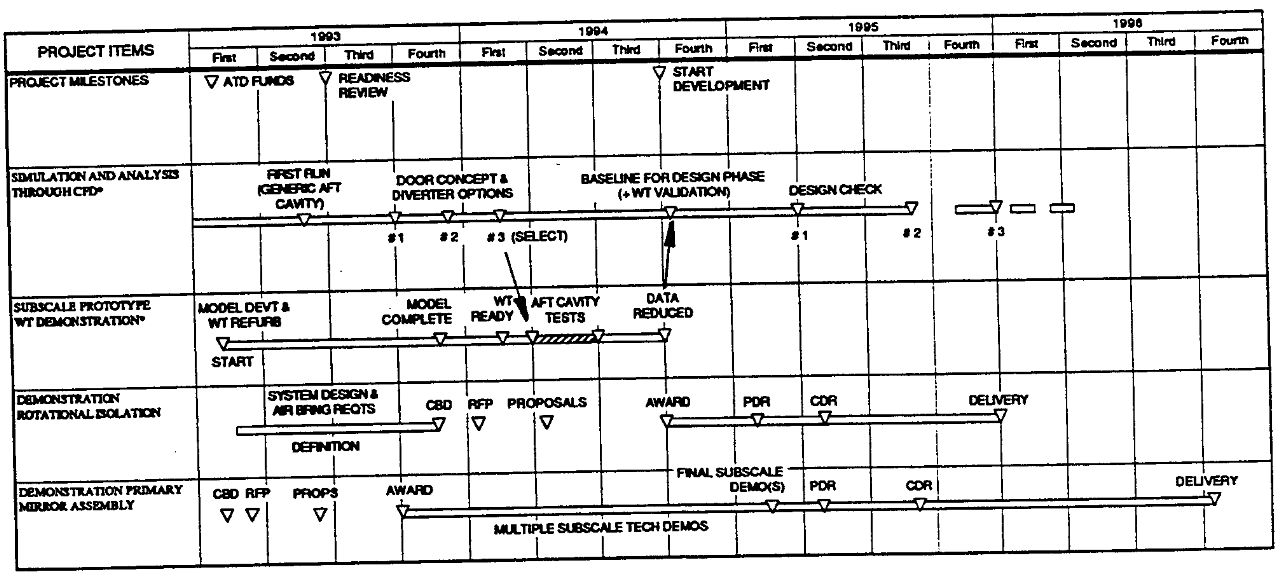
- Step 1 would consist of
    - construction of one or more sub-scale ultra light-weight mirrors, with areal density in the 30-60 kg/m^2 range or below;
    - achieving adequate mirror stiffness and strength under load (≥ 100 Hertz and ≈ 9 g, respectively) through suitable mounting technology.
    - If Step 1 is successful, contract activity would move on to Step 2.
    - If Step 1 is unsuccessful, contract activity would have to cycle back to a second phase of Step 1. A second Step 1 phase may require relaxing somewhat the weight constraints and reconsidering every technology innovation that was employed in the construction of the phase 1 sub-scale mirror:
        - mirror material, structure, and manufacturing process, without, however, sacrificing the original requirements of stiffness and strength.
        - It would also include assessing thoroughly the impact on the rest of the SOFIA project of any weight increase in the primary mirror.
- Step 2 might require
    - polishing the fast-figure, aspherical surface of the sub-scale mirror(s) to the SOFIA specifications, using any of a range of technologies.

- If Step 2 is successful, contract activity would move on to fabrication of a full-scale mirror blank, support assembly, generation of the figure, polishing, assembly, and test.

- If Step 2 is unsuccessful, contract activity would have to cycle back to a second phase of Step 2 and polishing alternatives; or, possibly, it may even require cycling through another phase of Step 1, followed, if successful, by another phase of Step 2.

Once Step 2 has been successfully concluded through final subscale demonstration, uncertainties in the fabrication of a full-scale primary mirror/mount that meets SOFIA's requirements still remain; for some of the technologies do not scale upward in a predictable fashion, such as the mirror support assembly performance and the generation of the figure. Thus, it is important that this pre-phase C/D demonstration activity be carried through to test at full-scale.

V. PROJECT MILESTONES AND FUNDING PROFILE



* Includes Active Cavity-Acoustic Quieting Technology Development and Demonstration

Figure 12. SOFIA project technology development schedule [approximate; see figures 7, 8, and 11 for details].

The demonstration active cavity-acoustic quieting technology and the spherical bearing and primary mirror assemblies will be specified at full size and flight-like designs to demonstrate realistically their performance capabilities. Provided funding is available, the demonstration assemblies will be designed to permit their upgrading to flight configuration and to allow them to serve as spare flight items.

	FY 1993	FY 1994	FY 1995	FY 1996
Shear Layer Control Demo	1.50	2.45	--	--
Cavity-Acoustic Quieting	0.20	1.00	1.00	--
Spherical Bearing/Isolation Demo	0.80	2.30	5.30	--
Primary Mirror Assembly Demo	2.50	6.00	6.50	3.00
Totals	5.00	11.75	12.80	3.00

Table 3. SOFIA technology funding profile in $ M.

VI. PROJECT MANAGEMENT

The management responsibility for the technology development tasks described in this plan will rest with a Study/Project Technologist, who will also be a Deputy Study/Project Manager and report to the Study/Project Manager. The Study/Project Technologist resides at the NASA center that has overall responsibility for the project.

As part of his or her responsibilities, the Study/Project Technologist will ensure that the technology development is technically sound, up-to-date, and within acceptable risk and cost, and that it meets the project's system engineering and integration requirements.

The goal of the technology development tasks is to determine and demonstrate the best possible technical solutions to the project's engineering and technical challenges. To achieve this goal, participation will be solicited from interested and capable parties at universities, industry, and Federal laboratories, including NASA centers. Consideration will be given to proposals ranging from traditional approaches, requiring only minor extensions beyond current technical capabilities, to radical approaches for solving the project's engineering and technical challenges.

It is anticipated that initially, for each task, parallel paths be pursued in solving the challenges; and that, in each case, from those paths the best solution be down-selected for final development and demonstration. Clear descriptions of these parallel paths, including milestones and decision points, as well as adherence to the schedule will be required. Teaming arrangements, possibly involving universities, industry, NASA centers, and other Federal laboratories, will be strongly encouraged.

VII. TECHNOLOGY TRANSFER POTENTIAL

Figure 13 presents SOFIA's technology transfer potential, along with similar potentials for three other Astrophysics missions.

Department of Commerce Emerging Technologies	Astrophysics Mission			
	AIM	SIRTF	SMIM	SOFIA
Advanced Materials	Driving		Using	
Superconductors		Using		
Advanced Semiconductor Devices	Using	Using	Using	
Digital Imaging Technology				Using
High-Density Data Storage	Using		Using	Using
High-Performance Computing	Using			Using
Optoelectronics	Driving			Using
Artificial Intelligence				
Flexible Computer-Integrated Mfg	Driving	Driving		Using
Sensor Technology	Driving	Driving	Driving	Using
Biotechnology				
Medical Devices and Diagnosis				

Key: Driving Technology / Using Technology

Figure 13. Technology transfer potential for SOFIA and three other Astrophysics missions.

Explanations and justification:

- Digital Imaging Technology:
  - Focal plane imager CCD with video tracking system.
  - Hartmann tester with computer optical alignment system.
- High-Density Data Storage:
  - Computational fluid dynamics, requiring in-core memories of approximately 90 M words and total data stored per CFD model of 2 G words, with approximately 5 CFD model calculations per year.
- High-Performance Computing:
  - Computational fluid dynamics, requiring at least 320 M flops throughput and capability up to 5 G flops.
- Optoelectronics:
  - Airborne fiber-optic databus.

- Flexible Computer-Integrated Manufacturing:
    - High-precision mirror polishing, including closed-loop test data input.
    - High-precision large spherical bearing surface figuring.
- Sensor Technology:
    - Pointing and control, including state-of-the-art zero-lock gyros.
    - Chopper, including high-precision inductive position sensors.

Explorers - FUSE

Program Manager:	John Lintott, NASA HQs
Program Scientist:	Ed Weiler, NASA HQs
Project Manager:	Jim Barrowman, GSFC
Project Technologist:	George Anikis, GSFC
Project Scientist:	Warren Moos, JHU

3/19/93

The FUSE (Far Ultraviolet Spectroscopic Explorer) mission is a Delta class Explorer. The FUSE mission will investigate basic astrophysical processes relative to the formation and development of the universe, its large scale structures, and the origin and evolution of stars and solar systems. The current observing program is to extend over a three year period. The mission primary scientific goal is to obtain high resolution spectra with unprecedented sensitivity from 912 to 1200 angstroms, measuring for the first time faint sources, both throughout our galaxy and at very large extragalactic distances. A secondary goal is to cover the region down to 100 angstroms. The combined wavelength range thus bridges the gap between that covered by HST and AXAF missions at moderate cost. The spectral window opened by this mission will provide unique access to many critically important species for astrophysics.

We now understand the technology required to accomplish this mission. In preparation for this mission, a wide range of important technical issues have been addressed in the Phase A study and during the current definition phase. The technical challenges are in the development of the FUSE telescope. Specifically, the areas which will require extensive study will be the telescope optics, detectors, and structure. Regarding the optics, previous studies by manufacturers have shown the fabrication is achievable; however, there remain certain processes that must be understood in the development of the optical surfaces. The requirements on the instrument structure impose very strict dimensional stability over large surfaces. Superior material such as graphite epoxy are under consideration and will be studied very thoroughly. The difficulties in construction of relatively large members and surfaces required to meet the stability requirements will be the focus of the effort. Finally, a program will be put in place to investigate the technical challenges and difficulties in the detector development. The detector system is one of the highest risk items in the instrument. A prototype will be developed and evaluated against the strict requirements of quantum efficiency, resolution, and dynamic range.

The Phase A study was completed in the summer of 1989. Since then, we have been in definition phase. The current plan is to start the Phase C/D in FY '95 and launch in FY 2000.

March 19.1993

Advanced Detector Research for Future NASA UV Missions

<u>Photoemissive detectors with microchannel plates and image readout</u>

- Detector systems are one of the highest risk areas in many flight instruments
- Judicious investment in detector technology can reduce risk/cost, and enhance success and capabilities of major missions, eg; EUVE photocathodes and readout. Research and enhancement of photocathode QE costs $1000's compared to $1,000,000's for equivalent mirror area increases.
- Photoemissive detectors identified as high priority by Astrotech 21, Advanced camera committee, Code SZ manifest.
- Applications include, FUSE, HST Advanced Camera, Lunar transit telescope, small payload satellites (SMEX), rocket experiments.
- Three main areas for future development:-

a)	Photocathodes	Increased QE, stability
b)	Microchannel plates	Increased resolution, dynamic range
c)	Readout and electronics	Increased resolution, dynamic range

Advanced Detector Research for Future NASA UV Missions

- **Photocathodes**
  - Current: - $\approx$50% QE for specific λ's in EUV, only few stable materials
  - Need: - $\geq$50% over most of EUV, extend into FUV, better stability
  - Approach: - new materials, systematic probe of physical/operational parameters, long term controlled stability testing
- **Microchannel Plates (MCP's)**
  - Current: - Standard; 10μm pores, rate $\leq$ 100 pore^{-1} sec^{-1}, background $\approx$1 event sec^{-1} cm^{-2}, 10% fixed pattern noise
  - Need: - 5 to 7μm pores, rate $\geq$1000 pore^{-1} sec^{-1}, background $\leq$0.002 event sec^{-1} cm^{-2}, $\leq$ 3% fixed pattern noise
  - Approach: - Promote MCP vendor research, evaluate small pore MCP formats, low resistance MCP stability/rate performance, push low radioactivity MCP development, evaluate new MCP fabrication techniques (advanced technology MCP's)
- **Readout and Electronics**
  - Current: - Delay line, formats 4000x1000 pixels (15x20μm), 10^5 c sec^{-1}
  - Need: - Formats 10 x 10cm, $\geq$5000 x 5000 pixels, $\approx 10^6$ c sec^{-1}
  - Approach: - New delay line designs (monolithic), new substrate structures & materials, fast interpolator electronics - develop hybrid, then ASIC design to increase rate, reduce size & power.

Advanced Detector Research for Future NASA UV Missions

Task Description — Development Goals

- Photocathodes:- Materials research & modeling, construct UHV deposition tank for photocathode fabrication & test vacuum chamber with monochromator, refurbish lifetest storage chamber. Deposit photocathodes and measure QE vs λ, θ, photoelectron energy and number distributions, long term stability measurements QE vs t (λ, θ, e^-).
  Costs:- 1993 - $100k, 1994 - $150k, 1995 - $100k

- Microchannel Plates:- Procure small pore ($<8\mu m$) MCP's, low noise MCP's, low resistance MCP's, advanced technology MCP's. Test flat field, resolution, rate limits, linearity, stability, gain, background and lifetime characteristics.
  Costs:- 1993 - $80k, 1994 - $150k, 1995 - $100k

- Delay Line Anodes and Electronics:- Develop designs for multilayer bidirectional & biplanar helical delay line anodes, examine high ε_r/low loss advanced substrate materials, commission laser/plasma etching station, fabricate anodes, bench/detector test [resolution, rate limits, integral & differential linearity, stability]. Design, fabricate, & test [resolution, rate limits, linearity, stability] 500kHz hybrid electronics, do design work on low power/mass ASIC electronics.
  Costs:- 1993 - $120k, 1994 - $200k, 1995 - $150k

FAX No.: 301-286-8709
Office No.: 301-286-8701

LASP

Laboratory for Astronomy and Solar Physics

To:

NAME	DATE AND TIME OF TRANSMISSION
MICHAEL KAPLAN	FEB. 22, 1993
NASA HQ, SZ	NUMBER OF PAGES 2 + TITLE PAGE

From:

NAME
GEORGE SONNEBORN

Reference:

SUBJECT
Detector Technology Development Charts

Message:

Mike-

These are the final version of the FUSE detector charts.

George

NASA/GSFC

GSFC

NEAR-TERM EXPLORER TECHNOLOGY DEVELOPMENT

Advanced UV Spectroscopy Detector

Objective: Develop and evaluate prototype high-resolution far-UV spectroscopy detector and hybrid electronics to demonstrate performance goals for future missions

Rationale:

- Detector systems are one of the highest risk areas in many flight instruments
- Judicious investment in detector technology can reduce mission risk/cost and enhance mission success
- Applicable to FUSE, SMEX, MIDEX, HST Advanced Camera
- Assured flight application of technology developments; FY93-FY95 effort supports FUSE Phase C/D start in FY95/96
- Encourages advanced microchannel plate development at multiple vendors
- Implemented through existing university and GSFC capabilities

Near-Term Goals for Technology Development (FY93-FY95):

- Photocathode materials - Improve quantum efficiency and long-term stability
  - Current: <40% QE for specific UV wavelengths, few stable materials
  - Near-term: ≥50% QE over 100-1200A range; better long-term stability
- Microchannel plates - Increase resolution and dynamic range; reduce background and fixed pattern noise
  - Current: 10μm pores; rate <<100 cts/pore/sec; dark count ~1/sec/cm2; 10% fixed pattern noise
  - Near-term: 8μm pores; rate ~200 cts/pore/sec; dark count <0.01/sec/cm2; ≤3% FPN
- Delay Line readout and electronics - Increase resolution and dynamic range
  - Current: Delay line formats - 4K x 1K pixels; 100K counts/sec
  - Near-term: 13 x 1cm format; 15K x 1K pixels; 300K counts/sec

NEAR-TERM EXPLORER TECHNOLOGY DEVELOPMENT

Advanced UV Spectroscopy Detector

Prototype Detector Characteristics: 13 x 1cm format; 15K x 1K pixels; local rate ~200 counts/pore/sec; global rate ~300K counts/sec; low fixed-pattern noise

Photocathode Tasks:

- Select and evaluate candidate photocathode materials for the far UV
- Upgrade ultrahigh-vacuum photocathode deposition tank; Refurbish lifetest storage chamber
- Measure photocathode QE vs. energy, wavelength, angle; Perform long-term (>2 yr) stability measurements

Microchannel Plate Tasks:

- Procure small pore (8μm), low resistance MCPs, small and large area formats, from multiple vendors
- Evaluate MCP performance (test flat field, resolution, rate limits, linearity, stability, gain, background, and life-time characteristics

Delay Line Anode and Electronics Tasks:

- Develop designs for high-resolution 2-D delay line anodes
- Commission laser/plasma etching station; Fabricate and bench test anodes
- Design, fabricate, and test 300 KHz hybrid electronics
- Integrate selected MCPs, anodes, electronics into prototype detector system; Test and evaluate

Proposed Funding: FY93 $400K FY94 $550K FY95 $450K

NASA
GODDARD SPACE FLIGHT CENTER
GREENBELT, MD. 20771

OPTICS BRANCH
CODE 717.1

FACSIMILE COVER SHEET

February 22, 1993

TO: Michael S. Kaplan

COMPANY: NASA Headquarters

FAX PHONE: 202-358-3096

OF PAGES (INCLUDING COVER): 3

SUBJECT: FUSE Telescope Technology view graphs per your request on 2/18/93

FROM: RITVA KESKI-KUHA
OPTICS BRANCH, NASA/GSFC

FAX PHONE: (301)286-2376

OFFICE PHONE: (301)286-6706

COMMENTS:

TECHNICAL AREA: Sensor Optics

TITLE: Ultraviolet and X-Ray Fabrication Technology

OBJECTIVE: Develop highly deterministic mirror fabrication processes for UV and x-ray mirrors that will 1) advance the state of the art in mirror quality, and 2) establish a process that manages program risk in the latter stages of the mirror fabrication cycle.

APPLICATION AND BENEFITS: The ion figuring system (IFS) developed by Eastman Kodak Co. has demonstrated a remarkable ability to bring mirror figures into spec with 1 or 2 iterations, as demonstrated on the Keck mirrors. GSFC is also using IFS to correct UV CVD-SiC mirrors for the SOHO mission. Problems encountered at GSFC with the IFS process applied to SiC justify the need to carefully evaluate material/mirror performance parameters before committing major program resources to the IFS process. Other new mirror fabrication processes, e.g. flow polishing, fall into this category and should be included in the study.

MILESTONES AND KEY PRODUCTS:

• Define program for specific materials (zerodur, ULE, etc.) and processes (IFS, flow polishing etc.); initiate procurements.	FY93
• Process demonstration on small mirrors and evaluate mirrors in the UV.	FY94
• Complete process demonstrations and evaluation in the UV, evaluate mirrors in x-ray region, initiate IFS demonstration on grazing incidence mirror.	FY95
• Complete grazing incidence IFS demonstration.	FY96

COMMERCIAL APPLICATIONS: Advancement in IFS and other fabrication processes for UV and x-ray mirrors will impact the quality of mirrors for the soft x-ray photolithographic systems planned for next generation microcircuit production.

ESTIMATED FUNDING ($K):

FY93	FY94	FY95	FY96
300	500	700	500

COLLABORATION:

Other Centers: MFSC will provide mirrors for grazing incidence demonstration

Industry: Eastman Kodak Co. for IFS: Baker Optics for flow polishing; HDOS for plasma assisted chemical etching.

University: University of New Mexico

Other Agencies: None Identified

TECHNICAL CONTACTS:

J. Osantowski	R. Keski-Kuha
NASA/GSFC	NASA/GSFC
Code 717.0	Code 717.1
301-286-3873	301-286-6706

HST Instrument ATD

Advanced technology investments in future HST instruments are high yield because they leverage optically correctable difraction limited 2.4 meter UV/visible/near IR mirror and already-built spacecraft and operations infrastructure

Past Accomplishments

- First successful development of a solar-blind Woods filter (originally proposed in 1930's) for the Wide Field and Planetary Camera 2
- Astronomical quality infrared HgCdTe technology developed by HST Near Infrared Camera was one of 1988's "most important stories in science" by Science News
- First successful demonstration of large format ultraviolet sensitive Multi Annode Microchannel Array (MAMA) detectors performed by Space Telescope Imaging Spectrometer team in November 1992

Hubble Space Telescope Instrument Program
Advanced Technology Development

HST's unique capabilities for visible wide field imaging and ultraviolet spectroscopy and imaging will not be challenged by ground based 8m telescopes or adaptive optics during its lifetime (Science Institute Advanced Camera study panel)

Detectors for Advanced Camera (1999) required by 1996

Solar blind photon counting detectors including the multi annode microchannel array and delay line readout

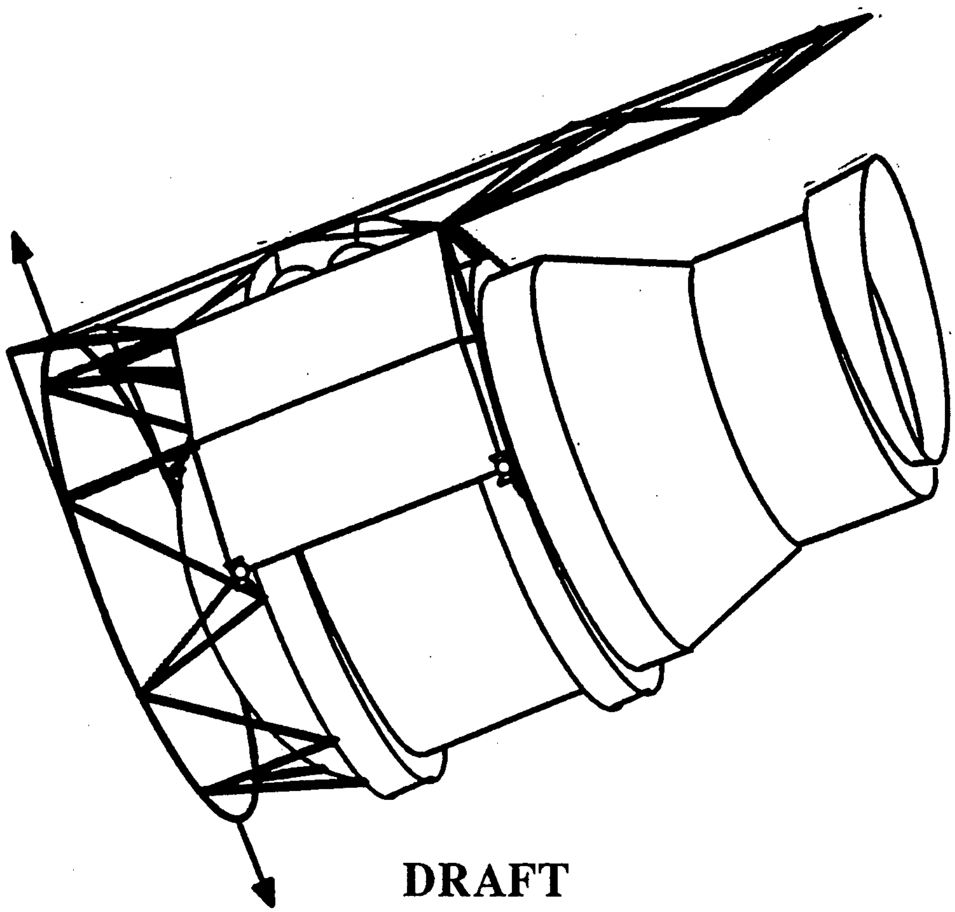
Solar Blind filters - Development required to follow-up on first successful demonstration of Woods filter technology

Charged Coupled Devices - Astronomical quality UV-sensitive 2K x 2K chips, with both 15 and 7.5 micron pixels

Augmentation estimate of $6 million total through FY 1996 (spread over at least two years, the earlier the better)

TECHNOLOGY PLAN
for
SIRTF

Space Infrared Telescope Facility



DRAFT

March 19, 1993

To be submitted to Gregory Reck

Associate Administrator
Office of Advanced Concepts and Technology
NASA Headquarters

Dr. Peter B. Ulrich
SIRTF Program Manager
Astrophysics Division

Michael S. Kaplan
Acting Chief
Advanced Programs Branch
Astrophysics Division

SIRTF

Program Manager:	Pete Ulrich, NASA HQs
Program Scientist:	Larry Caroff, NASA HQs
Project Manager:	Jim Evans, JPL
Project Technologist:	Rich Capps, JPL
Deputy Project Technologist	Craig McCreight, ARC
Project Scientist:	Mike Werner, JPL

3/19/93

TABLE OF CONTENTS

SIRTF TECHNOLOGY PLAN

I. INTRODUCTION

The purpose of this plan is to provide the Office of Advanced Concepts and Technology (OACT, formerly OAST) with the near-term technology needs for the Space InfraRed Telescope Facility (SIRTF). SIRTF is the highest priority new program in the Astrophysics Division in the 1990's. It was named the highest priority new program for all astronomy by the National Research Council Astronomy and Astrophysics Survey Committee (the Bahcall Committee) as well as being the highest priority new "Flagship Mission" recommended by the Space Science and Applications Advisory Committee (SSAAC). It completes the Great Observatory series, adding the vital two decades of coverage (i.e., a factor of 10^2) in the electromagnetic spectrum from 2-200 micrometers. Because of its urgency and importance to the Astrophysics Division, this plan is being submitted separately from, and ahead of, the Astrophysics Division plan for technology in support of all future astrophysics missions.

SIRTF is presently planned for a new start in the second half of the 1990's, with technology developments aimed at maintaining a new start option as early as FY96. Essential to its premier capabilities as a long-term space observatory are the latest in infrared focal plane array and cryogenic optical technology, which contribute to the 1,000 to 10,000 gain in performance of SIRTF over prior infrared space missions, including the Infrared Astronomy Satellite (IRAS), Cosmic Background Explorer (COBE), and the European Space Agency (ESA) Infrared Space Observatory. These technologies have been fruitfully co-sponsored in the past by both OSSA and OAST funding. Now, with the planned new start in the second half of this decade (along with the possibility of a Non-Advocate Review as early as FY94), it is time to address the requisite enabling technologies for SIRTF. This plan solicits OACT's support for this increased technology support in the critical FY93-96 time-frame. Besides infrared focal plane array and cryogenic optical technology, information systems related technology is also included in this plan to support the increased information from advanced focal plane arrays and the more complex observing scenarios planned for SIRTF.

II. ORGANIZATION OF THE PLAN

The plan is organized around the three technologies areas mentioned above: Infrared Focal Plane Array Technology, Cryogenic Optical Technology, and Information Systems Technology. For each topic under each of these areas, the following format is followed: Title, Objective, Applications/Missions Enabled, Required Technology, Payoff/Performance, Existing Efforts, and Issues. Following the discussion of each technology area, a major milestone schedule and funding requirements are given for that technology area. In the concluding section of this plan, summary funding requirements and technology priorities are given.

III. INFRARED FOCAL PLANE ARRAY TECHNOLOGY

A. TITLE: Extrinsic Silicon (Si:x) Impurity Band Conduction (IBC) Detectors

A.1 OBJECTIVE: Develop and demonstrate optimized IBC detector array technology for use in the ~5 to 40 micrometer (μm) range. Demonstrate excellent sensitivity, low dark current, freedom from anomalous effects, and adequate format sizes.

A.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, IRST-NG, NGST, II

A.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
	1. Optimized Si:As IBC detector arrays (~5 -28 μm)	128 x 128 Si:As, with non-optimized material and non-optimum readout. Recently fabricated; not yet characterized.	Fully characterized, optimized 128 x 128 array. Optimum doping concentration, doping profile, readout technology, antireflection coating. Quantum Efficiency (QE)> 30%. Radiation effects established. Breadboard demo completed. Feasibility of 256 x 256 formats established.	June 1995
	2. Optimized Si:Sb IBC detector arrays (~5 - 40 μm)	Discrete Si:Sb detectors, with epitaxially-grown layers (both blocking and IR active). Work beginning on producing Si:Sb detectors in backside-illuminated 10 x 50 format.	(same as above, except response to 40 μm required)	June 1995

A.4 PAYOFF/PERFORMANCE:

-Large formats --> increased wide field imaging capability
-Wide spectral response --> single IBC material replaces two earlier non-IBC Si candidates
-Extended cutoff wavelength (Sb) --> access to important spectral features between 28 and 40 μm
-Radiation immunity --> less corruption of data; eliminates need to thermally anneal detectors
-Linear response --> greatly simplified post-detection processing

A.5 EXISTING EFFORTS:

-Si:As initial development (approx. 50% OSSA/SIRTF & 50% OACT): Rockwell International + Cornell University
Additional lab characterization at Ames.

-Si:Sb feasibility and initial development (approx. 50% OSSA/SIRTF & 50% OACT): Rockwell International + Cornell University

A.6 ISSUES:

-Details of radiometric performance need to be studied under low-background (lab and observation)

B. TITLE: Extrinsic Germanium (Ge:x) Impurity Band Conduction (IBC) Detectors

B.1 OBJECTIVE: Develop and demonstrate optimized IBC detector array technology for use in the ~30 to 200 μm range. Demonstrate excellent sensitivity, low dark current, freedom from anomalous effects, producibility, and adequate format sizes.

B.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, SMIM, IRST-NG, LDR, SMMI

B.3

	REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1.	Optimized Ge:Ga IBC detector arrays (~40 - 200 μm). Produced via epitaxy	Discrete Ge:Ga detectors, with epi-produced layers (blocking and IR-active). Backside-illumination demonstrated. Low QE, and limited (~180 μm) long-wave cutoff.	Fully characterized, optimized arrays for SIRTF. Formats: 32 x 32, 16 x 32, & 2 x 16 for photometer; 4 x 32 & 2 x 8 for spectrograph. QE > 30%. Radiation effects established. Breadboard demo completed.	June 1995
2.	Optimized Ge:B (or other?) IBC detector arrays (~30 - 200 μm). Produced via ion implantation	Discrete Ge:B detectors. Ion-implanted IR active layer over pure blocking layer. Low QE, but excellent dark current shown.	(same as above)	June 1995

B.4 PAYOFF/PERFORMANCE:

-Wide spectral response --> single IBC material replaces at least two earlier non-IBC and non-monolithic Ge candidates
-Radiation immunity --> IBC offers major improvement over bulk Ge detectors; much less corruption of data; eliminates need to thermally anneal detectors
-Planar detector geometry --> Eliminates need for complex mechanical stressing rig in 120-200 μm range
-Linear response --> greatly simplified post-detection processing

B.5 EXISTING EFFORTS:

-Ge:Ga initial development (approx. 10% OSSA/SIRTF & 90% OACT/JPL): Rockwell International + JPL.
Additional lab characterization at U. Rochester.

-Ge:B feasibility and initial development (approx. 10% OSSA/SIRTF & 90% OAST/Ames): Lawrence Berkeley Laboratory (LBL)

B.6 ISSUES:

-Details of radiometric performance need to be studied under low-background (lab and observation)
-Low-temperature readout technology needed

C. TITLE: Extrinsic Germanium (Ge:x) Bulk Photoconductive Detector Arrays

C.1 OBJECTIVE: Develop and demonstrate optimized Ge:x (stressed and unstressed) detector array technology for use in the ~30 to 200 μm range. Demonstrate excellent sensitivity, low dark current, freedom from anomalous effects, reproducibility, producibility, and adequate format sizes.

C.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, SMIM, IRST-NG, LDR, SMMI

C.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1. Optimized Ge:Ga bulk detector arrays (~50 - 120 μm).	Discrete Ge:Ga detectors, and 3 x 32 pathfinder "Z-plane" array. Low QE. Readout type not determined. Imaging characteristics not known. Radiation effects of real concern. No flight-compatible construction technology.	Fully characterized, optimized arrays for SIRTF. Formats: 32 x 32 for photometer; 4 x 32 for spectrograph. QE > 30%. Radiation effects understood. Breadboard demo completed.	June 1995

2.	Optimized stressed Ge:Ga bulk detector arrays (~120 - 200 µm).	Discrete Ge:Ga detectors, and small (up to 8 x 8, handwired). Low QE. Readout type not determined. Imaging characteristics not known. Radiation effects of real concern. No flight-compatible construction technology.	Fully characterized, optimized arrays for SIRTF. Formats: 2 x 8 for photometer; 2 x 16 for spectrograph. QE > 30%. Radiation effects understood. Breadboard demo completed.	June 1995
3.	Optimized Ge:Be bulk detector arrays (~30 - 50 µm).	Discrete Ge:Be detectors. No proven array technology, with techniques suitable for flight. Planar array approach modeled, but just now starting exploratory hardware phase (4 x 16 pathfinder arrays).	Fully characterized, optimized arrays for SIRTF. Formats: 16 x 32 for photometer; 4 x 32 for spectrograph. QE > 30%. Radiation effects established. Breadboard demo completed.	June 1995

C.4 PAYOFF/PERFORMANCE:

-2-d array formats --> efficient mapping of far-IR sources and regions
-Spectral coverage --> various dopants in bulk Ge provide coverage over nearly three octaves in wavelength
-Planar detector geometry --> (for Ge:Be, and possibly for Ge:Ga) allows efficient packaging, photolithographic production techniques
-Very low dark current --> Enables very long integrations

C.5 EXISTING EFFORTS:

-Ge:Ga detector material development (OSSA/SIRTF supported) @ Lawrence Berkeley Lab. Characterization at U. Arizona. Development of pathfinder 3 x 32 arrays at U. Arizona.

-Stressed Ge:Ga detector material development (OSSA/SIRTF supported) @ Lawrence Berkeley Lab. Characterization at U. Arizona. Development of stressing harnesses at LBL, U. Arizona, and Cornell.

-Ge:Be detector material development (OSSA/SIRTF supported) @ Lawrence Berkeley Lab. Characterization at U. Arizona. Development of pathfinder 4 x 16 array: small contract at Rockwell Autonetics.

C.6 ISSUES:

-Packaging: demonstration and space qualification of stacked arrays
-Low-temperature readout technology needed
-Details of radiometric performance need to be studied under low-background (lab and observation)
-Radiation effects critical

D. TITLE: Low-temperature, Low-noise Readout Technology

D.1 OBJECTIVE: Develop and demonstrate optimized cryogenic preamplifiers and multiplexers with extremely low noise, low power dissipation, low leakage, and excellent stability. Demonstrate freedom from excess noise, and adequate format sizes.

D.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, SMIM, NGST, IRST-NG, II

D.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
Optimized Si MOSFET readouts for SIRTF instruments	Readouts for hybrid arrays, with excess noise components, and read noise levels in the 50 - 100 electron (e-) range. Many FET readouts require elevated temperatures (e.g., 20 K) to avoid freezeout effects commonly seen at liquid helium temperatures. Cascade circuits partly successful (low noise, but require 20 K operation).	Fully characterized, optimized low temperature. readouts. Need 1 x 32 and n x 32 arrays, with 3 e- read noise, operating at 1.5 K, for photometer. Camera and spectrograph require. 128 x 128 and 256 x 256 readouts with < 10 e- read noise, and 4 K operating temp. Radiation effects established. Breadboard hybrids characterized.	June 1995

D.4 PAYOFF/PERFORMANCE:

-Low noise --> achievement of background-limited sensing, and ultimate scientific return
-Low temperature operation --> solves major packaging problem, particularly in SIRTF Ge channels. Operation at 1.5 K allows hybrid, planar assembly of Ge BIB or Ge:x PC detectors.
-Low power dissipation --> extends mission lifetime, and eliminates "glow" from focal plane readouts.
-Radiation immunity --> less corruption of data; eliminates need to thermally anneal detectors
-Linear response --> greatly simplified post-detection processing

D.5 EXISTING EFFORTS:

-Si MOSFETs: Phase 1 low-temperature readouts, first designs on thin Si epi. (approx. 30% OSSA/SIRTF & 70% OACT): Valley Oak Semiconductor + TRW. Lab characterization at U. Arizona, Ames, and GSFC.

-Si MOSFETs: Phase 2 low-temperature readouts, enhancement of 1 x 32 readout on thin Si epi. (approx. 90% OSSA/SIRTF & 10% OACT): Valley Oak Semiconductor + TRW. Lab characterization at U. Arizona, Ames, and GSFC.

D.6 ISSUES:

-What are fundamental limits of noise?
-Details of radiometric performance need to be studied under low-background (lab and observation)

E. TITLE: Improved Indium Antimonide (InSb) Detector Array Technology

E.1 OBJECTIVE: Develop improved InSb detector array technology for use in the ~1 to 5 μm range. Achieve 2x or higher increase in fill factor over state-of-the-art. Demonstrate ability to reliably fabricate high-performance arrays in formats of 256 x 256 and larger.

E.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, NGST, II

E.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1. Optimized InSb detector arrays (~1 - 5.5 μm)	Developmental 256 x 256 InSb arrays produced, but not characterized. Mesa diode process used, with fill factor of ~30%. Excellent QE and low noise seen in smaller arrays.	Fully characterized, optimized 256 x 256 array. Optimum diode design, with fill factor in excess of 80%. Proven production capability. QE > 60%. Anti-reflection coating proven. Radiation effects established. Low dark current demonstrated (< 1 e-/s). Breadboard demo completed. Feasibility of 512 x 512 formats established.	June 1995

E.4 PAYOFF/PERFORMANCE:

-Large formats --> increased mapping capability
-Flat spectral response --> uniform coverage of 1 - 5 μm region
-Proven mesa technology --> provides SIRTF with access to excellent InSb diodes (proven on COBE, Galileo, ground-based observations)
-Low dark current --> allows long integrations, limited by frequency of particle hits
-High quantum efficiency --> detection of extremely faint sources, in critical 3 - 5 μm cosmic window

E.5 EXISTING EFFORTS:

-InSb initial development (90% OSSA/SIRTF & 10% OACT): Santa Barbara Research Center. Detailed lab characterization at U Rochester. (Baseline approach for SIRTF/IRAC)

-InSb developmental array production (30% OSSA/SIRTF & 70% OACT): Cincinnati Electronics. Detailed lab characterization at Kitt Peak National Observatory and JPL. (Proposed alternate approach)

E.6 ISSUES:

-Details of radiometric performance need to be studied under low-background (lab and observation)

F. TITLE: Far-Infrared Filter Technology

F.1 OBJECTIVE: Develop and demonstrate optimized far-infrared metal mesh filter technology for use in the > 30 μm range. Demonstrate excellent transmissivity, low out-of-band leakage, narrow bandpass, stability upon repeated cooling to liquid helium temperatures, reliable producibility, and ruggedness for flight.

F.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, SMIM, IRST-NG, LDR, SMMI

F.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1. Both narrowband and high- or low-pass high-performance IR filters for > 30 μm.	Prototype far-IR filters for ISO fabricated and demonstrated. Performance established in 30 - 120 μm range.	Fully characterized, optimized far-IR filters for 30 - 200 μm range. Transmission > 70%, with excellent out-of-band rejection. Survives repeated cooldowns to ~1.5K Breadboard demo completed.	June 1995

F.4. PAYOFF/PERFORMANCE:

-High transmission --> greater sensitivity of instruments in far IR. Filter technology critical to overall instrument performance
-Out-of-band blocking --> eliminates the need for other optical elements; greatly simplifies data reduction
-Low-temperature performance --> allows isothermal instruments and focal planes to be developed, with significant savings in cost and complexity

F.5 EXISTING EFFORTS:

-Metal mesh filter development (~70% OSSA funds to the Smithsonian Air and Space Museum plus ~30% U.S. Naval Research Lab funds for fabrication)

F.6 ISSUES:

-Construction technology
-Temperature cycling effects
-Details of performance needs to be studied under low-background, low-temperature conditions (lab and observation)
-Low temperature characterization facilities

G. FUNDING SUMMARY/MAJOR MILESTONE SCHEDULE

The funding requirements for SIRTF-related Infrared Focal Plane Array technology is given in Table 1 and the major milestone schedule in Figure 1.

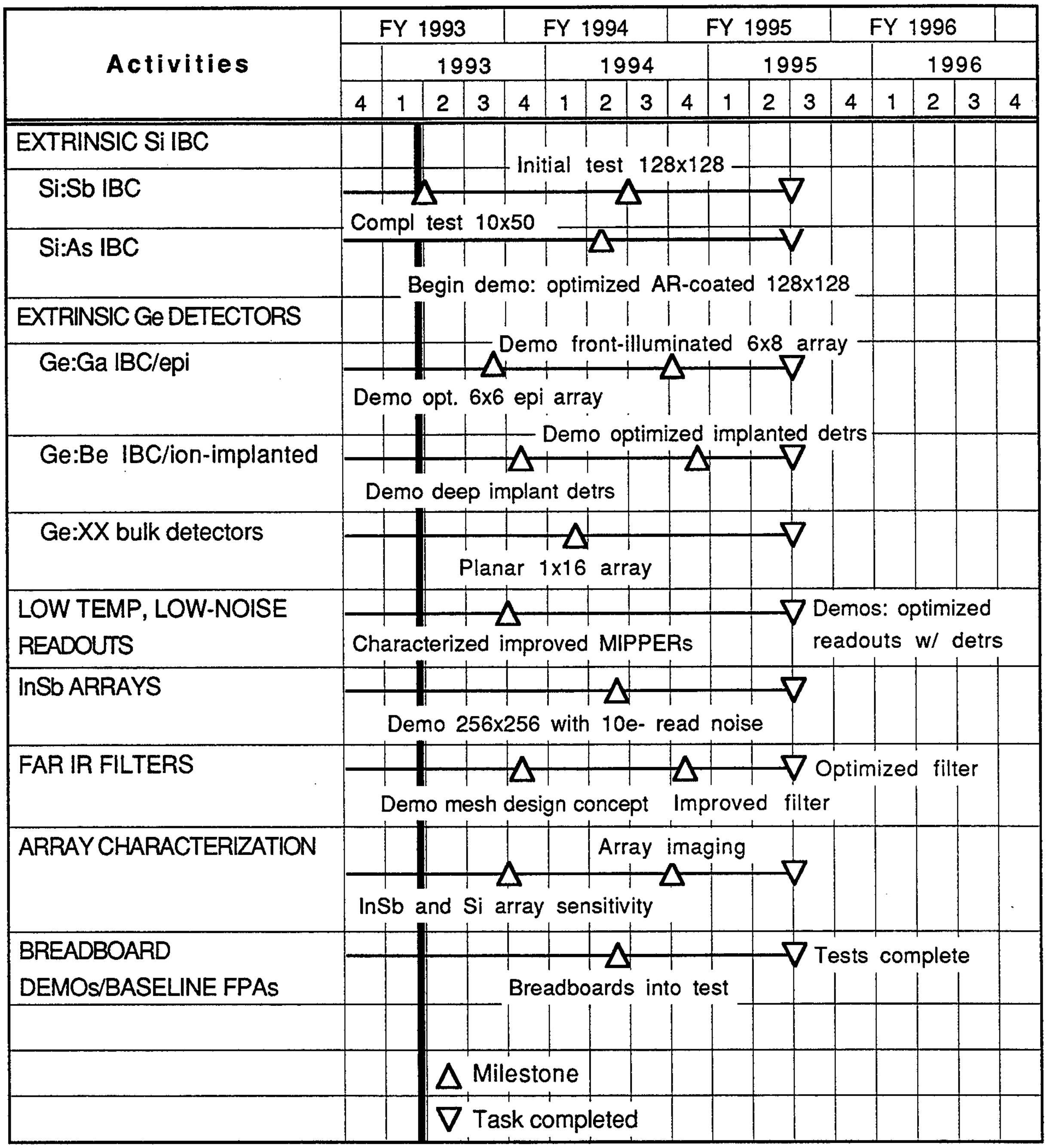
SIRTF TECHNOLOGY FUNDING REQUIREMENTS
INFRARED FOCAL PLANE ARRAYS (FPAs)

	FY93			FY94			FY95			FY96		
TECHNOLOGY	ITP	AUG	SZ	ITP	AUG	SZ	ITP	AUG	SZ	ITP*	AUG	SZ**
Extrinsic Si IBC Detectors												
Si:Sb IBC	$80K	$300K	$570K	$90K	$400K	$578K	$100K	$300K	$724K	$120K	---	---
Si:As IBC	$60K	$250K	$180K	$50K	$250K	$193K	$60K	$100K	$240K	$40K	---	---
Extrinsic Ge Detectors												
Ge:xx IBC (epitaxy)	$350K	$100K	$150K	$350K	$475K	---	$350K	$300K	$150K	$350K	---	---
Ge:xx IBC (ion implant)	$90K	$150K	---	$90K	$150K	---	$90K	$100K	---	$90K	---	---
Ge:xx Bulk Detectors	---	$200K	$1,107K	---	$225K	$1,162K	---	$100K	$926K	---	---	---
Low-Temperature, Low-Noise Readout Technology	$280K	$350K	$200K	$270K	$400K	---	$200K	$100K	$300K	$200K	---	---
InSb Arrays	$40K	$200K	$1,219K	$20K	$200K	$2,644K	---	---	$1,471K	---	---	---
Far-Infrared Filters	---	$100K	---	---	$100K	---	---	$50K	---	---	---	---
Array Characterization	$70K	$300K	---	$100K	$250K	---	$130K	$150K	---	$130K	$150K	---
Breadboard Demos of Baseline FPAs	---	---	---	---	---	---	$40K	$200K	---	$40K	$250K	---
TOTALS	$970K	$1,950K	$3,426K	$970K	$2,450K	$4,577K	$970K	$1,400K	$3,811K	$970K	$400K	---

* Continuation of program for other applications (LDR, etc.)
** Assumes instruments begin Phase C/D one year before observatory

FIGURE 1

MAJOR MILESTONE SCHEDULE
INFRARED FOCAL PLANE ARRAYS



3/19/93

IV. CRYOGENIC OPTICAL TECHNOLOGY

A. TITLE: Cryogenic Optical Telescopes

A.1 OBJECTIVE: To extend the state-of-the-art in mirrors, mirror mounts and image quality testing to enable telescopes with apertures as large as one meter that perform acceptably in the few Kelvin range, and that are flight qualifiable.

A.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, ...

A.3

	REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1.	1 meter diameter, light-weight cryogenic aspheric mirrors	6 μm diffraction limited performance at 4.2K, 0.5 meter diameter spherical mirror (fused quartz)	5 μm diffraction limited performance at 6K. Stable coefficient of thermal expansion. Low areal mass density. High stiffness to mass density. Either can be cryo-null figured or (preferrably) does not require cryo-null figuring. Demonstrate compatiable flight qualifiable mirror mounting technology.	1996
2.	Cryo testing facility and methods	0.7 meter spherical mirror at 4.2K (NASA Ames)	Up to 1 meter aspherical mirrors at 2K.	1995
3.	Mirror coatings	No adequate coating for the 2 to 200 μm spectral range	High reflectance, low scattering, 2 to 200 μm, 2K operating temperature	1996
4.	Telescope structures	All beryllium structure (IRAS)	Match to mirror material, suitable for passive thermal-ization, light weight, high stiffness to mass density.	1996

A.4 PAYOFF/PERFORMANCE:

High angular and spectral resolution, provides high efficiency in a discovery mission. Lightweight materials reduce overall launch weight, allowing for better performance and/or less expensive launch vehicles.

A.5 EXISTING EFFORTS:

1. Under SIRTF funding, NASA Ames has tests underway on both fused quartz, and lightweighted fused quartz for mirrors up to 0.5 meters.

2. Under OACT funding, silicon carbide coupons are being evaluated for fundamental material properties.

3. Both IRAD and DoD programs have sponsored lightweight mirror developments of appropriate size in fused quartz, beryllium and silicon carbide but not for 2K operation.

A.6 ISSUES

1. Timely selection of candidate materials is important to SIRTF.

2. Continued participation by Ames in supporting cryo mirror testing is necessary for the SIRTF development schedule.

B. TITLE: Far Infrared Stray Light Control

B.1 OBJECTIVE: Develop and demonstrate technology of a black coating for stray light control in the wavelength range of 0.5 to 200 µm: measure its hemispherical bi-directional reflectance function, qualify it for spaceflight, and develop a process specification for its application to large surface areas; and, using measured BDRF data, predict stray light performance in typical applications and verify prediction by test.

B.2 APPLICATIONS/MISSIONS ENABLED: SIRTF, ...

B.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQM'T	DATE
1. BRDF measurement	In-plane-of-incidence BDRF measurements complete to 500 µm on candidate coating, Ames 24E.	Obtain out-of-plane-of incidence measurements to obtain hemispherical BRDF data. Verify BDRF at 4K.	April 93
2. Valid candidate coating (Ames 24E or derivative thereof) for cryo-flight environment	Coupon qualification completed including some cryogenic testing: basis for selection of Ames 24E.	Extend technology to large surface areas representative of actual coating applications. Qualification test for cryo-flight environment.	April 94

3.	Develop process specification		Develop specifications and demonstrate its applicability to typical IR applications.	Oct. 94
4.	Verification of straylight prediction.	Computer programs for straylight prediction are fully developed Predictions of straylight performance have been made using in-plane-of-incidence BDRF data.	Extend computer code to use hemispherical BDRF to verify straylight prediction through test article.	April 95

B.4. PAYOFF/PERFORMANCE:

Straylight control essential in order to achieve background limited IR detection.

B.5 EXISTING EFFORTS:

NASA Ames is currently doing BDRF plane-of-incidence measures. Have capability to 700 µm. NASA Ames facility is unique.

B.6 ISSUES:

Straylight predictions don't agree with experience; that is, straylight is always greater than predicted.
Mehanical adherence of coatings to surface during vibration testing has been a problem.

C. FUNDING SUMMARY/MAJOR MILESTONE SCHEDULE:

The funding requirements for SIRTF-related Cryogenic Optical technology is given in Table 2 and major milestone schedules in Figures 2 and 3.

TABLE 2

SIRTF TECHNOLOGY FUNDING REQUIREMENTS

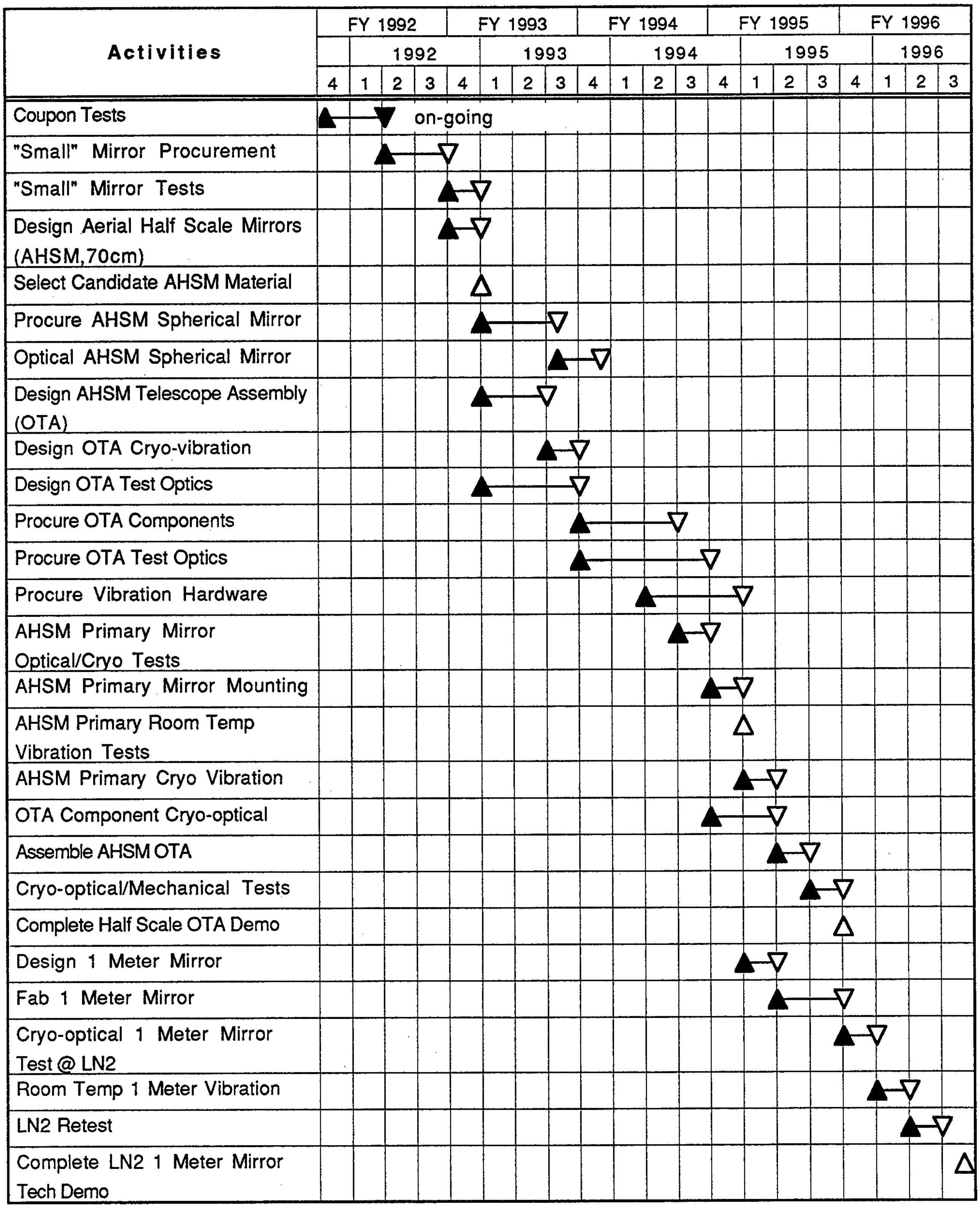
CRYOGENIC OPTICAL TECHNOLOGY

Technology	FY 93	FY 94	FY 95	FY 96
Cryogenic Optical Telescopes	$1,000K	$2,500K	$2,000K	$2,000K
Far-Infrared Straylight Control	$275K	$275K	$350K	-------
TOTALS	$1,275K	$2,775K	$2,350K	$2,000K

3/19/93

FIGURE 2

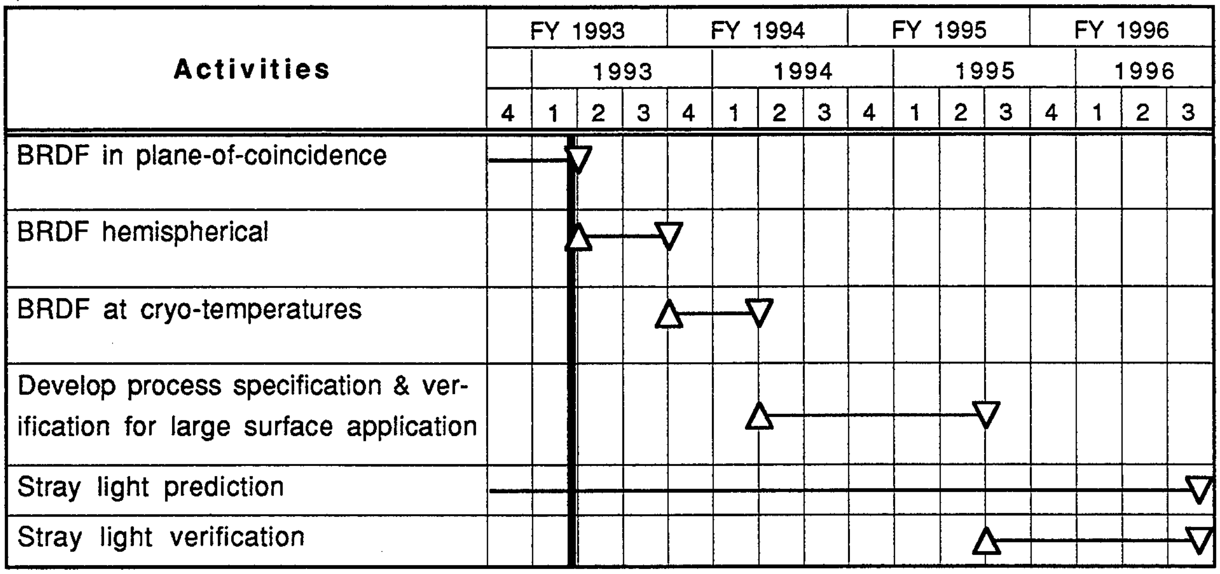
MAJOR MILESTONE SCHEDULE
CRYOGENIC OPTICAL TELESCOPES



3/19/93

FIGURE 3

MAJOR MILESTONE SCHEDULE
FAR INFRARED STRAYLIGHT CONTROL



V. INFORMATION SYSTEMS TECHNOLOGY

A. TITLE: Spacecraft Operability Model

A.1 OBJECTIVE: Develop a set of design requirements to specify on future flight systems (spacecraft and payload) which are likely to be affordable impacts to the cost of the flight system and will result in a less costly and /or more capable ground system and operations.

A.2 APPLICATIONS/MISSIONS ENABLED:

SIRTF and potential benefit to all subsequent future missions.

A.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQM'T	DATE
1. Identification of spacecraft/payload characteristics that have made past missions difficult/expensive to operate.	There is a wide body of informal opinions from past mission experience across NASA, but no documented compendium.	Historical data base of flight system operability characteristics.	Oct. 93
2. An assessment of feasibility for a proposed set of operability specifications.	None exists.	Survey industry and NASA spacecraft/ payload builders for an assessment of the practicality of a proposed set of operability specifications.	Oct. 94
3. Operability design requirements in a form spacecraft/ payload designers can respond to with engineered designs and costs.	No verified technical specification for "operability" exists.	A verified technical specification for spacecraft payload operability.	April 95 (In time for inclusion in SIRTF system RFP for an Oct. 95 new start).

A.4 PAYOFF/PERFORMANCE:

The payoff of this proposed work could enable operability to be a design parameter from the very beginning of the detailed design process, reducing overall project cost, and enabling a lower cost operations phase freeing up funds for subsequent missions.

A.5 EXISTING EFFORTS:

No formal work in process.

A.6 ISSUES:

As mission objectives have grown more complex, ground systems and operations costs have climbed becoming a greater percent of total mission cost. A major factor has been the identification of flight system operability design issues too late in the design/implementation process to allow affordable changes to the design.

B. TITLE: Data Compression Pre-processing/On-board Image Processing

B.1 OBJECTIVE: Develop the pre-processing algorithms and practical implementation schema to enable SIRTF to utilize the data compression chips developed in the OACT program.

B.2 APPLICATIONS/MISSIONS ENABLED:

SIRTF, plus any subsequent mission with similar noise characteristics in its raw instrument data.

B.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1. Characterize the raw data likely from SIRTF IR arrays.	Does not exist at the level needed.	Data characteristics expected for the IR arrays which will require compression.	April 93
2. Algorithms for matching the IR array data to one or both of the compression chip algorithms.	None exists.	Algorithms which would assure at least 2 to 1 compression using the variable compression techniques already developed.	Oct. 93

3.	Assess practical implementation approach	N/A	Determine if an affordable flight computer can handle the pre-processing algorithm or if another custom chip is required.	April 94
4.	Demonstration of successful compression with actual IR data	N/A	Assuming a practical algorithm is found, demonstrate its practical realization before final telecom design is specified.	April 95

B.4 PAYOFF/PERFORMANCE:

In descoping SIRTF to reduce its expected cost data rate goals have been lowered > factor 2 under the assumption that information preserving data compression will be available. The custom chips for data compression researched under the OACT program and being flight qualified for future projects do not look directly compatible with IR array characteristics when used for astronomical data (perhaps <<2 achieved compression ration). Preprocessing of the data may make the chips usable. Failure to solve the system problem could result in nearly a 50% reduction in data return.

B.5 EXISTING EFFORTS:

One or both of the compression chips are to be flight qualified by other programs.

B.6 ISSUES:

Whether an algorithm exists which would enable $\geq$ factor 2 compression, and whether the algorithm can be realized in an affordable flight computer. If another custom chip is required as to pre-processor than earlier identification is required to allow for development time or a modification of the telecommunications design.

C. TITLE: Design Phase Automated Information Capture

C.1 OBJECTIVE: Provide the means to capture the detailed design during the design/implementation phase and the resulting characteristics during the Test and Integration phase for a mission. The information captured in a form that enables automated utilization by knowledge based systems for support of operations in the diverse areas of fault isolation and recovery, sequence generation and verification, and sustaining of flight system software. The information would also be directly accessed by personnel for similar purposes.

C.2 APPLICATIONS/MISSIONS ENABLED:

SIRTF, but the capability described would benefit literally all future missions.

C.3 REQUIRED TECHNOLOGY

	REQUIRED TECHNOLOGY	CURRENT SOA	REQ'T	DATE
1.	Evaluate and plan the use of emerging automated info and knowledge capturing techniques.	Info capture involves manual effort by experts familiar with the target applications software.	Evaluation of potential techniques for automating information capture applicable to the flight system design process.	April 93
2.	Demonstrate applicability to flight system design. Assess practical implementation approach	N/A	Demonstrate feasible approaches to design data capture.	April 94
3.	Provide requirements for design data capture. Continue effort to demonstrate feasibility for ground system and integration and test phase.	N/A	Provide requirements for design capture. Continue previous work to see if same or different approach required for ground system and integration and test phase.	April 95 (In time incorporate in SIRTF System RFP to support an Oct. 95 start.)

C.4 PAYOFF/PERFORMANCE:

Every mission must deal with the handing off of the flight system from the expert designer/builders to the expert operators. This involves a transfer (usually incompletely handled) by after-the-fact, manually-generated "users guides". Also use of expert systems/knowledge based systems in operations has been inhibited by the difficult error-prone, incomplete job of manually constructing the rules/knowledge base.

C.5 EXISTING EFFORTS:

Some theoretical work not directly related to flight systems design.

C.6 ISSUES:

Can a way be found to automate (or at least provide tools that greatly facilitate) the capture of design, as-build, and test data which can be levied on a system contractor responsible for the development of the flight system?

D. FUNDING SUMMARY/MAJOR MILESTONE SCHEDULE:

The funding requirements for SIRTF-related Information Systems technology is given in Table 3 and the major milestone schedule in Figure 4.

TABLE 3

SIRTF TECHNOLOGY FUNDING REQUIREMENTS

INFORMATION SYSTEMS TECHNOLOGY

Technology	FY 93	FY 94	FY 95	FY 96
Spacecraft Operability Model	$140K	$160K	$80K	---
Data Comparison Pre-processing/ On-board Image Processing	$140K	$160K	$225K	---
Design Phase Automated Information Capture	$140K	$160K	$180K	TBD
TOTALS	$420K	$480K	$485K	TBD

VI. SUMMARY

While all of the above discussed technologies are critical to enabling a SIRTF C/D new start in the second half of this decade, some are more critical than others. Table 4 shows priorities for the technologies discussed in this plan. The technologies are grouped into three classifications: the highest priority, higher priority, and high priority. The rankings are similar to previous priorities provided to OAST/OACT with the major exception of Si:Sb IBC infrared focal plane arrays being included in the highest priority category because it provides capability not available with Si:As IBC arrays in the scientifically critical 28-40 μm portion of the infrared spectrum. Lower ranked technologies, while critical, were either more mature or already had significant funding planned in the OAST/OACT baseline or had significant funding support from other agencies such as DoD. A major exception is the Ge:x IBC development where, without OACT support, work will likely be dropped even though the potential gain for the SIRTF program is large. In the case of cryogenic optical telescope technology, ranked in the highest priority category, funding requested supports the development of only a single material half scale and full scale mirror with the choice of material being based on the results of coupon testing. Additional funding would be highly desirable to allow the possibility of two materials being carried to the half scale mirror level of development. The inclusion of a second material half scale mirror could be an important consideration if, for example, the second material were silicon carbide which offers significant weight and thermal advantages for SIRTF, yet could be dropped after coupon testing because of an assessed greater risk in achieving larger sizes that maintain figure at cryo temperatures than fused quartz, the present SIRTF baseline.

Table 5 provides a funding summary for all three technologies discussed in this plan. Planned OSSA SIRTF ATD funding is also shown to illustrate how OACT SIRTF technology funding complements OSSA funding in both technology and mission definition for SIRTF.

FIGURE 4

MAJOR MILESTONE SCHEDULE
INFORMATION SYSTEMS TECHNOLOGY

Activities	FY 1993				FY 1994				FY 1995				FY 1996			
		1993				1994				1995				1996		
	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
SPACECRAFT OPERABILITY MODEL																
Identification of past missions spacecraft/ payload operability characteristics	△			▽												
Development feasibility assessment					△			▽								
Publish flight system operability specifications							△			▽						
DATA COMPRESSION PRE-PROCESSING/ ON-BOARD IMAGE PROCESSING																
Characterize IR arrays	△	▽														
Develop algorithm			△	▽												
Evaluate implementation					△	▽										
Demonstrate performance on real IR data							△			▽						
DESIGN PHASE AUTOMATED INFORMATION CAPTURE																
Approaches for automating design capture	△	▽														
Feasibility demonstration for flight system design capture			△			▽										
Specification for flight system design capture										▲						
Extend work to ground system and integration and test							△									▽

3/19/93

TABLE 4

SIRTF TECHNOLOGY PRIORITIZATION

Highest Priority

Low-Temperature, Low-Noise Readout Technology
Si:Sb IBC
Cryogenic Telescopes
Array Characterization

Higher Priority

Extrinsic Ge Detectors:
- Ge:x IBC (epitaxy),
- Ge:x IBC (ion implant),
- Ge:Ga Bulk Detectors

Breadboard Demos of Baseline FPAs
Far-Infrared Straylight Control
Far-Infrared Filters

High Priority

Si:As IBC
Ge:Be Bulk Detectors
InSb Arrays
Spacecraft Operability Model
Data Compression Pre-processing/On-board Image Processing
Design Phase Automated Information Capture

TABLE 5

SIRTF TECHNOLOGY FUNDING SUMMARY

OAST FUNDING

Technology		FY 93	FY 94	FY 95	FY 96
Infrared Focal Plane	ITP*	$970K	$970K	$970K	$970K
	(augmentation)	$1,950K	$2,450K	$1,400K	$300K
Cryogenic Optics	(augmentation)	$1,275K	$2,775K	$2,350K	$2,000K
Information Systems	(augmentation)	$420K	$480K	$485K	TBD
TOTALS		$970K+ $3,645K augmentation	$970K+ $5,705K augmentation	$970K+ $4,235K augmentation	$970K+ $2,300K + TBD

OSSA SIRTF ATD FUNDING

Instrument Technology	FY 93	FY 94	FY 95	FY 96
• Infrared Focal Plane	$3,426K	$4,577K	$3,811K	-----------
• IRAC Optics	$84K	$609K	$148K	-----------
• IRAC Mechanism	$69K	$512K	$57K	-----------
• IRAC Calibrator	$144K	$87K	-----------	-----------
• IRS/MIPS Cryo Mechanism	$200K	$200K	$200K	-----------
Observatory Studies/Technology	$3,577K	$1,515K	$10,784K	$5,000K
Mission Definition	$500K	$7,500K	$10,000K	$15,000K
TOTALS:	$8,000K	$15,000K	$25,000K	$20,000K

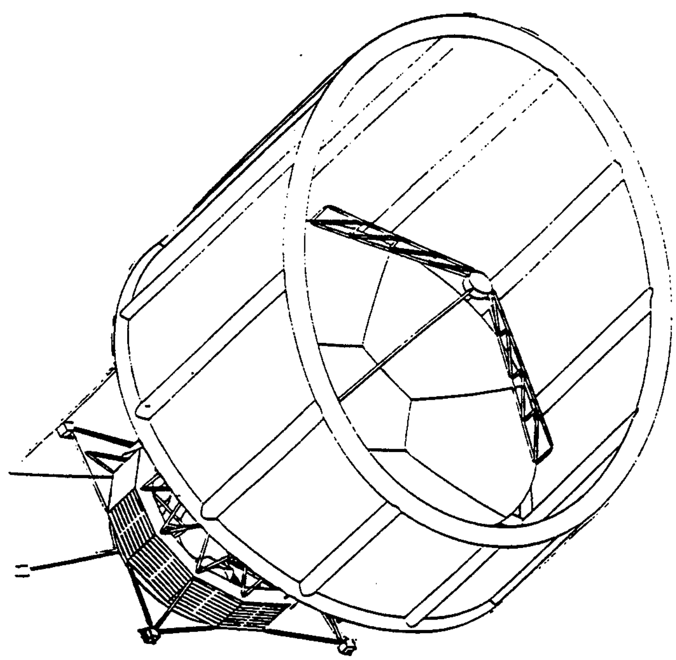
IRAC = Infrared Array Camera
IRS = Infrared Spectrometer
MIPS = Multiband Imaging Photometer

*Level shown is planned in FY93 and assumed to be level for FY 94, 95 and 96.

SMIM/FIRST

Submillimeter Intermediate Mission/
Far Infrared Space Telescope

TECHNOLOGY PLAN



DRAFT

March 19, 1993

To be submitted to Gregory Reck

Associate Administrator
Office of Advanced Concepts and Technology
NASA Headquarters

Michael S. Kaplan
Acting Chief, Advanced Programs Branch
Astrophysics Division

SMIM/FIRST

Study Manager:	Mike Kaplan, NASA HQs
Study Scientist:	Larry Caroff, NASA HQs
Study Manager:	Bill Gray, JPL
Study Technologist:	Gary Parks, JPL
Study Scientist:	Sam Gulkis, JPL

3/19/93

Table of Contents

I. INTRODUCTION

The purpose of this plan is to provide OACT with the near-term technology needs for the submillimeter astrophysics mission originally called SMIM (Submillimeter Intermediate Mission). This mission has been selected by the Astrophysics Division, and endorsed by the Space Science and Applications Advisory Committee (SSAAC), as the highest priority mission after SIRTF in the 1990's. At the same time, the European Space Agency (ESA) has been studying a submillimeter mission known as the Far Infrared Space Telescope (FIRST). This is a more ambitious mission than SMIM, with a larger aperture and longer lifetime. Due to financial constraints, ESA has considered descoping FIRST. An alternative to descoping would be to enter into a collaboration with NASA. The Astrophysics Division is actively investigating this possibility, and has identified a menu of possible contributions to a joint mission, tentatively dubbed SMIM/FIRST. Because of the importance of a submillimeter mission to the Astrophysics Division, and to concentrate in a single document the technology requirements of any such mission, this plan is being submitted separately from the overall Astrophysics Division plan for technology in support of all future astrophysics missions.

SMIM/FIRST would have a new start by the end of the decade, probably around 1997-1998. Fundamental to opening the submillimeter region of the electromagnetic spectrum with high spectral and spatial resolution is the development of Superconductor-Insulator-Superconductor (SIS) heterodyne receivers in the 400-1200 GHz range, and lightweight, low-cost composite telescope materials. GaAs Schottky mixers, the current alternative to SIS mixers, require two to three orders of magnitude more local oscillator output power, and integration time would have to be increased by a factor of four to provide the required sensitivity. Currently the required power output for SIS mixers has been demonstrated at 600 GHz, and similar techniques are expected to meet the requirements at higher frequencies. The composite mirror technology, in which the United States has a clear lead for low-temperature applications, significantly reduces the cost of the telescope, as well as allowing smaller, cheaper launch vehicles for a given mission, further reducing total mission cost. In the collaborative mission options under investigation, the NASA contribution would include the heterodyne instruments and the panels for the telescope (see section IV). Both OSSA and OACT have sponsored development of these technologies in the past, and have met with considerable success: The Submillimeter Sensors Program and the Precision Segmented Reflector (PSR) Program have achieved major advances in the basic technologies. Continued support is critical to maintain the U. S. lead in these technologies, and to enable NASA to build or collaborate in SMIM/FIRST.

Two applications on SMIM/FIRST can benefit from work being done under the SIRTF technology plan for extrinsic Germanium (GE:x) Impurity Band Conduction (IBC) detectors. This technology, useful in the 30-200 micron spectral region in the form of monolithic planar arrays, will exhibit low dark currents and quantum efficiencies near 30%. The benefits for SMIM/FIRST are the following:

The Far Infrared Spectrometer uses a baseline detector consisting of a linear array of silicon bolometers cooled to 0.1 K by an adiabatic demagnetization refrigerator (ADR). The bandwidth is from 85 to 180 microns. The IBC devices could be used in place of the bolometers, and offer the advantages that they are easily implemented as one-dimensional arrays, and only require cooling to 1.5 K to achieve the bolometer NEP (noise-equivalent power) performance. This could eliminate the need for an ADR, resulting in substantial savings

The second potential application for the SIRTF IBC detectors would be as a fine calibration sensor (FCS). The FCS would be used for periodic calibration of the fine guidance sensor (star tracker) to the focal plane by centroiding in a small (10 x 10) IBC array located in the focal plane.

II. ORGANIZATION OF THE PLAN

The plan is organized around the two technology areas mentioned above: SIS Heterodyne Radiometers and Optical Systems. For each topic under each of these areas, the following format is followed: Title, Objective, Applications/Missions Enabled, Required Technology, Payoff/Performance, Existing Efforts, and Issues. Following the discussion of each technology area, a major milestone schedule and funding requirements are given for that technology area. In the concluding section of this plan, summary funding requirements and technology priorities are given.

III. SIS HETERODYNE RECEIVER TECHNOLOGY

The focal plane sensors for the SMIM/FIRST mission require sensitive heterodyne receivers covering the frequency range from 400 to 1200 GHz. The heterodyne receiver mixes the submillimeter wave signal from a remote source with a local oscillator (LO) signal, converting it to a lower frequency signal with considerably improved energy resolution. The difference or intermediate frequency (IF) is in the microwave region, where it is amplified and sent to the broadband spectrometer for spectral analysis. Key elements of the heterodyne receiver requiring development are the mixer, the local oscillator, the IF amplifier, and the IF spectrometer.

An important figure of merit for a heterodyne receiver system is the receiver noise temperature. The lower the noise temperature the more sensitive the receiver. Theoretically the lowest noise temperature that can be achieved corresponds to a fluctuation of one photon. This limit, known as the quantum limit, corresponds to an equivalent noise temperature of $h\nu/k$ (h is Planck's constant, ν is the frequency, and k is Boltzmann's constant). The emphasis for astrophysics applications is on producing components that will result in receivers with performance between 10 and 50 times the quantum limit.

The technology readiness demonstration goals are driven by the following mission schedules, based on a new start (phase C/D) for SMIM/FIRST in 1998.

Technology readiness demonstration goals for SMIM/FIRST:	Performance T_{rx} (DSB)	Date
Initial laboratory heterodyne receiver near 600 GHz	2000 K	1992
Initial laboratory heterodyne receiver near 800 GHz	4000 K	1994
Optimized laboratory heterodyne receiver near 600 GHz	800 K	1995
Initial laboratory heterodyne receiver near 1200 GHz	5000 K	1996
Optimized laboratory heterodyne receiver near 800 GHz	1000 K	1997
Optimized laboratory heterodyne receiver near 1200 GHz	1500 K	1998

(T_{rx} = receiver temperature)

These are specifications for receiver performance. Component specifications are discussed in the following sections.

To achieve these ambitious goals, a very aggressive technology development effort is required. The development of the active devices and passive circuits in the mixers and multipliers needs to be closely coupled.

IV. TECHNOLOGY DEVELOPMENT TASKS

A work breakdown structure has been developed based on the Astrotech 21 Submillimeter Advisory group recommendations. The proposed work breakdown structure with individual program elements are listed in Table III.

Table III. Work Breakdown Structure

- 1.0 Superconducting Mixer Development
  - A. Superconducting Materials
  - B. SIS Tunnel Junctions
  - C. Superconducting Mixer Embedding Circuit Development
  - D. Open Structure Mixer Mounts
- 2.0 Solid State Local Oscillator Development
  - A. High-frequency Varactor Development
  - B. High-frequency Multiplier Circuits
  - C. Moderate Power First Stage Multiplier
- 3.0 Receiver Development
  - A. SIS Receiver Systems
  - B. Focal Plane Mixer Array Development
- 4.0 IF Amplifier Development
- 5.0 Innovative Approaches for Submillimeter Wave Sensors (NRA)
  - A. New Concepts for Detection at Submillimeter Wavelengths
  - B. New Concepts for Submillimeter Wave Local Oscillators
  - C. New Superconducting Materials for Submillimeter Wave Applications
  - D. New Semiconducting Materials for Submillimeter Wave Applications
  - E. New Circuit and Coupling Concepts
  - F. Array Detection Concepts

1.0 Superconducting Mixer Development

High-sensitivity, heterodyne mixers are required to carry out planned astrophysics submillimeter wave missions. SIS tunnel junction mixers have been identified as the best approach to achieve the performance required. The single-element mixers for SMIM/FIRST, spanning the frequency range from 400 to 1200 GHz, will use superconducting Nb or NbN SIS tunnel junctions in waveguide mounts below about 700 GHz, and open structure mounts at the higher frequencies. Focal plane arrays of superconducting mixers are required for long-term applications, such as LDR.

TABLE 1

SMIM/FIRST TECHNOLOGY FUNDING REQUIREMENTS
SUPERCONDUCTING MIXER DEVELOPMENT

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
A. Superconducting Materials	450	473	496	521	547
B. SIS Tunnel Junctions	500	525	551	579	608
C. Superconducting Mixer Embedding Circuit Development	300	315	331	347	365
D. Open Structure Mixer Mounts	300	315	331	347	365
TOTALS	1550	1628	1709	1794	1884

A. Superconducting Materials

A.1 OBJECTIVE: The objective of this task is to develop superconducting and barrier materials for use in tunnel junctions for the frequency range required by SMIM/FIRST, 400 to 1200 GHz. Emphasis will be placed on frequencies above 700 GHz, where superconductive devices have not been demonstrated.

A.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

A.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	1. Nb/AlOx/Nb	mixers with $T_{mix} < 10$ $h\nu/k$ for frequencies < 500 GHz -mixers with $T_{mix} = 60$ $h\nu/k$ for 630 GHz	mixers with $T_{mix} < 10$ $h\nu/k$ for frequencies < 800 GHz	9/95
	2. NbN/MgO/NbN	mixers with $T_{mix} < 30$ $h\nu/k$ for frequencies < 210 GHz	mixers with $T_{mix} < 10$ $h\nu/k$ for frequencies < 1200 GHz	9/97
	3. Alternative materials systems		mixers with $T_{mix} < 10$ $h\nu/k$ for frequencies < 1200 GHz	9/97

(T_{mix} = mixer temperature)

A.4 PAYOFF / PERFORMANCE

$T_{mix} < 10$ hν/k	->	currently meet requirement below 500 GHz, to enable SMIM/FIRST to reach 1200 GHz
Increased frequency	->	access to important spectral features between 500 and 1200 GHz

A.5 EXISTING EFFORTS

Superconducting material development (NbN/MgO) is funded by NASA OACT and SDIO ISTC (this funding ends in FY 93) at JPL

A.6 ISSUES: The technology needs of SMIM/FIRST require device technologies to operate optimally at the intrinsic limits of the current materials systems. The ultimate high-frequency limits of SIS mixers are set by 1) the gap frequency ($\nu_g = E_g/h$, where h is Planck's constant) near which superconducting RF losses are expected to increase, and 2) the inherent junction relaxation time, which results in an equivalent RC roll-off in performance. The intrinsic limits of both these parameters are determined by the superconductor and insulator materials in the SIS structure. The gap frequency is determined by the choice of superconductor, and scales roughly with its superconducting transition temperature, while the relaxation time is determined by the insulator barrier, and, for a given insulator, has an intrinsic minimum value when it is one monolayer thick. The gap frequency of Nb is about 700 GHz; for NbN it is about 1500 GHz.

Characteristics of the current materials systems (Nb/AlO_x/Nb and NbN/MgO/NbN) need to be more fully understood and optimized. In addition, since this technology is breaking new ground, new superconductor and insulator materials need to be explored. Among the candidate superconductor systems are NbTiN alloys and a member of the high-T_c family of superconductors BaKBiO. Barriers of interest are SiC and oxidizable refractory nitride overlayers.

B. SIS Tunnel Junctions

B.1 OBJECTIVE: The objective of this task is the fabrication of SIS mixer elements suitable for testing various RF embedding circuits (waveguide and quasioptically coupled) and mixer array concepts using the best currently available materials. Two systems are being developed, Nb-based tunnel junctions of the form Nb/AlO_x/Nb, and NbN-based tunnel junctions of the form NbN/MgO/NbN. Reliable techniques for the fabrication of submicron-area SIS tunnel junctions from state-of-the-art materials systems need to be developed.

B.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

B.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	1. Nb/AlOx/Nb to 600 GHz	-mixers with $T_{mix} < 10$ hν/k for frequencies < 500 GHz -mixers with $T_{mix} = 60$ hν/k for 630 GHz -integrated tuning stubs -submicron sizes	-mixers with $T_{mix} < 10$ hν/k -integrated tuning stubs -submicron sizes	9/95
	2. NbN/MgO/NbN to 600 GHz	-mixers with $T_{mix} < 30$ hν/k for frequencies < 210 GHz	-mixers with $T_{mix} < 10$ hν/k -integrated tuning stubs -submicron sizes	9/95
	3. Nb/AlOx/Nb 600 to 800 GHz*		-mixers with $T_{mix} < 10$ hν/k -integrated tuning stubs -submicron sizes	9/97
	4. NbN/MgO/NbN 600 to 800 GHz*		-mixers with $T_{mix} < 10$ hν/k -integrated tuning stubs -submicron sizes	9/97
	5. NbN/MgO/NbN 800 to 1200 GHz		-mixers with $T_{mix} < 10$ hν/k -integrated tuning stubs -submicron sizes	9/98

* At some frequency in the range 600 to 800 GHz, Nb-based junctions will no longer perform well. At that point NbN-based junctions are predicted to become the device of choice. This transition point is not currently known, so that both types of junctions need to be developed. (T_{mix} = mixer temperature)

B.4 PAYOFF / PERFORMANCE

$T_{mix} < 10$ hν/k -> currently meet requirement below 500 GHz, to enable SMIM/FIRST to reach 1200 GHz

Increased frequency -> access to important spectral features between 500 and 1200 GHz

integrated tuning stubs -> broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for mixers

submicron sizes -> appropriate impedance for tuning circuits

B.5 EXISTING EFFORTS

Superconducting mixer development funded by NASA OAST at JPL, funded by OSSA at U. Va.

B.6 ISSUES: Need to provide SIS tunnel junctions for RF test of mixer mounts being developed throughout the 400 to 1200 GHz range. In addition, need to continue to develop and refine the fabrication process for junctions using the state-of-the-art materials systems developed above.

C. Superconducting Mixer Embedding Circuit Development

C.1 OBJECTIVE: The objective is the development and characterization of superconductive electronics for use in heterodyne mixer embedding circuits at 400 GHz to 1200 GHz. In particular, design approaches need to be developed for the superconducting tuning circuit integrated with the SIS tunnel junction. This is required to achieve 10% RF fixed tuned instantaneous bandwidth. Included is the characterization of properties, such as RF surface losses, phase velocity dispersion on planar transmission lines, magnetic and Josephson penetration depths, RF current distribution, energy gap effects, and AC Josephson phenomena, required to design mixer embedding circuits.

C.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

C.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	Nb tuning circuits to 600 GHz	-mixers with $T_{mix} = 60$ hν/k -3% bandwidth	-mixers with $T_{mix} < 10$ hν/k -10% bandwidth	9/95
	NbN tuning circuits to 600 GHz		-mixers with $T_{mix} < 10$ hν/k -10% bandwidth	9/95
	NbN tuning circuits to 800 GHz		-mixers with $T_{mix} < 10$ hν/k -10% bandwidth	9/97
	NbN tuning circuits to 1200 GHz		-mixers with $T_{mix} < 10$ hν/k -10% bandwidth	9/98

(T_{mix} = mixer temperature)

C.4 PAYOFF / PERFORMANCE

$T_{mix} < 10$ hν/k	->	currently meet requirement below 500 GHz, to enable SMIM/FIRST to reach 1200 GHz
Increased frequency	->	access to important spectral features between 500 and 1200 GHz
integrated tuning stubs	->	broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for mixers

C.5 EXISTING EFFORTS
OSSA SMIM technology support at JPL, OSSA Astrophysics funding, SDIO funding

C.6 ISSUES: Important materials parameters and circuit design techniques must be characterized at high frequencies. In particular, dispersion and loss in superconductive transmission lines must be accurately known. Magnetic penetration depth, film thickness, and dielectric constants also need to be accurately known. Techniques for calculating planar circuit parameters such as characteristic impedance, and strip inductance above 400 GHz must be developed. This includes methods for analyzing RF current distributions. Precise techniques are required, since the Q of the circuit is generally high. Approaches to designing integrated tuning stubs to maximize performance and bandwidth are required.

D. Open Structure Mixer Mounts

D.1 OBJECTIVE: The objectives are to define and develop planar antenna, integrable mixer mounting structures for high-efficiency RF and IF coupling between the input and output signal ports and the SIS tunnel junction. At frequencies above about 700 GHz, a mechanically machined waveguide becomes very difficult to fabricate without high losses. Open structure mixer mounts are predicted to be the approach-of-choice.

D.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

D.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	Open structure mounts to 600 GHz	T_{rx} = 20 hv/k at 230 GHz T_{rx} = 20 hv/k at 500 GHz	-mixers with T_{rx} < 10 hv/k -10% bandwidth - integrated tuning stubs	9/95
	Open structure mounts to 800 GHz		-mixers with T_{rx}< 10 hv/k -10% bandwidth -integrated tuning stubs	9/97
	Open structure mounts to 1200 GHz		-mixers with T_{rx} < 10 hv/k -10% bandwidth -integrated tuning stubs	9/98

(T_{rx} = receiver temperature)

D.4 PAYOFF / PERFORMANCE

T_{mix} < 10 hv/k	->	currently meet requirement below 500 GHz, to enable SMIM/FIRST need to push capability to 1200 GHz
Increased frequency	->	access to important spectral features between 500 and 1200 GHz
integrated tuning stubs	->	broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for mixers

D.5 EXISTING EFFORTS
NASA OAST Submillimeter Sensors Program at JPL and Caltech

D.6 ISSUES: Key issues in the design and implementation of the integratable mixer mount are (1) the development of efficient, low-loss antenna coupling structures with high beam efficiency in coupling to the SMIM/FIRST optical elements, (2) the implementation of integrated tuning structures for broad band SIS junction impedance matching at the signal and local oscillator frequencies, and (3) the design of simple low-loss optical diplexing circuitry.

2.0 Solid State Local Oscillator Development

The power required to operate an SIS tunnel junction mixer is 50-100 μW; about 1 mW is required to drive a single GaAs Schottky diode mixer or an array of SIS tunnel junctions.

SMIM/FIRST requires frequency-agile local oscillators tuning over the frequency band from 400 to 1200 GHz. These must have adequate power (about 50 to 100 μW) to drive the SIS tunnel junction mixers. The baseline approach identified for SMIM/FIRST is to used solid state millimeter wave oscillators followed by frequency multipliers. At least two stages of multiplication will be required. For example, 900 GHz could be generated by a 100 GHz Gunn oscillator, followed by a tripler to 300 GHz, and a second tripler to 900 GHz. The requirements for the two multiplier stages are somewhat different. The first stage handles moderate power levels, having an input power of about 50 to 100 mW and an output power of about 5 to 10 mW. On the other hand, the second stage is a low power multiplier with input power levels of 5 to 10 mW and output power levels of 50 to 100 μW.

TABLE 2

SMIM/FIRST TECHNOLOGY FUNDING REQUIREMENTS
SOLID STATE LOCAL OSCILLATOR DEVELOPMENT

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
A. High-frequency Varactor Development	450	473	496	521	547
B. High-frequency Multiplier Mounts	450	473	496	521	547
C. Moderate Power First Stage Multiplier	450	473	496	521	547
TOTAL	1350	1418	1488	1563	1641

A. High-Frequency Varactor Development

A.1 OBJECTIVE: The objective of this task is to develop planar varactor diodes for operation as the second stage of multiplication with output frequencies in the range 500 to 1200 GHz and output powers of 50 to 100 μW.

A.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

A.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	500 to 600 GHz 100 μW 10% bandwidth planar devices	-GaAs Schottky varactors -100 μW at 600 GHz -whisker contacted - 3% bandwidth	500 to 600 GHz 100 μW 10% bandwidth planar devices	9/95
	600 to 800 GHz 100 μW 10% bandwidth planar devices		600 to 800 GHz 100 μW 10% bandwidth planar devices	9/97
	800 to 1200 GHz 50 μW 10% bandwidth planar devices		800 to 1200 GHz 50 μW 10% bandwidth planar devices	9/98

A.4 PAYOFF / PERFORMANCE

Increased output power -> Adequate power for coupling into SIS tunnel junctions mixers in SMIM/FIRST receiver configuration (including loss in frequency multipliexer and signal/LO diplexer)

Increased frequency -> access to important spectral features between 500 and 1200 GHz

Increased bandwidth -> broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for local oscillators

Planar devices -> SMIM/FIRST has baselined multipliers in the chains; whisker contacted devices are very difficult to space-qualify in these numbers

A.5 EXISTING EFFORTS: Internal JPL funding through DDF

A.6 ISSUES: The technical issues fall into three categories; (1) semiconductor materials development, (2) device processing development, and (3) device characterization and modeling. The current semiconductor material used is GaAs. Faster materials, such as InAs, may be needed for high-frequency performance. In addition the device structure, that is, the layers and dopings, need to be optimized for high-frequency performance. The device processing is critical. Planar devices have not been demonstrated above about 100 GHz. They are limited, in part, by parasitics associated with the interaction of the device and its substrate and leads. Fast micro-structure approaches, combined with circuit integration, need to be developed. Understanding of the device physics in the submillimeter wave range is in its infancy. A strong device modeling and measurement effort, including both theoretical approaches using basic physics and empirical approaches using large signal equivalent circuits, is critical to addressing the performance of the devices at high frequencies.

B. High-Frequency Multiplier Circuits

B.1 OBJECTIVE: The objective is to develop triplers and quintupler mounts for the high-frequency 2nd stage multipliers with output frequencies in the range from 500 to 1200 GHz and with output power of 50 to 100 μW for a fixed tuned bandwidth of 10%.

B.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

B.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	500 to 600 GHz 100 μW 10% bandwidth	-100 μW at 500 GHz whisker contacted devices -crossed waveguide mounts - 3% bandwidth	500 to 600 GHz 100 μW 10% bandwidth	9/95
	600 to 800 GHz 100 μW 10% bandwidth		600 to 800 GHz 100 μW 10% bandwidth	9/97
	800 to 1200 GHz 50 μW 10% bandwidth		800 to 1200 GHz 50 μW 10% bandwidth	9/98

B.4 PAYOFF / PERFORMANCE

Increased output power -> Adequate power for coupling into SIS tunnel junctions mixers in the SMIM/FIRST receiver configuration (including loss in frequency multipliexer and signal/LO diplexer)

Increased frequency -> access to important spectral features between 500 and 1200 GHz

Increased bandwidth -> broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for local oscillators

B.5 EXISTING EFFORTS: OAST Submillimeter Sensors Program at JPL and the University of Massachusetts, internal JPL funding through DDF, OSSA Astrophysics at the University of Massachusetts

B.6 ISSUES: Multiplier issues include (1) circuit design at input, output, and idler frequencies including integrated tuning elements, (2) circuit fabrication and device integration, and (3) multiplier characterization and modeling. Current circuits employ mechanically machined crossed waveguide mounts with whisker contacted devices. Integrated tuning elements need to be developed to replace the whisker. With planar devices, the multiplier design can be much more flexible, allowing integration of part of the circuit with the device. This will lead to broader band frequency designs, a requirement of SMIM/FIRST. Circuit fabrication needs to be developed in conjunction with device fabrication so as to take advantage of the integration of the circuit with the device. It is critical to understand loss mechanisms in the circuit through a combination of large signal analysis, scale modeling, and multiplier characterization.

C. Moderate Power First Stage Multiplier

C.1 OBJECTIVE: The objective of this task is to generate sufficient local oscillator power in the near submillimeter wavelength range to drive a second stage of multiplication to higher frequencies. The goal will be to generate about 30 mW of power at 300 GHz in one or two multiplication stages.

C.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

C.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	GaAs Schottky planar diode based multipliers	20 mW at 160 GHz	30 mW to 300 GHz 10% band width	9/96

C.4 PAYOFF / PERFORMANCE

Increased output power	->	Adequate power to drive second multiplier
Increased frequency	->	access to important spectral features between 500 and 1200 GHz
Increased bandwidth	->	broad instantaneous bandwidth; SMIM/FIRST requires 10% fixed tuned bandwidth for local oscillators

C.5 EXISTING EFFORTS: Internal JPL DDF at the University of Massachusetts and the University of Virginia

C.6 ISSUES: One key objective is to replace the traditional whisker contacted varactor diode with an integrated series array of varactors. This approach not only allows increased power handling capacity, but also circuitry will be developed and optimized so as to maximize flexibility. Traditional waveguide mounts will be used to test the new diode concepts and, if successful, less traditional all-planar circuitry may be developed.

3.0 Receiver Development

SMIM/FIRST needs to develop 10% bandwidth, fixed-tuned mixers with an IF bandwidth of 10 GHz. Broadband mixer mounts with an appropriate combination of waveguide and integrated tuning structures must be developed. In addition, the broad bandwidth IF requirements will require improved IF matching circuits.

Focal plane arrays greatly enhance the data-taking capability in a given period of time. Though SMIM did not require arrays, SMIM/FIRST will have such a requirement, since FIRST, which was designed to observe only specific frequencies, could support an array receiver. Further, observing runs of limited duration, e.g., from aircraft or balloon platforms, will greatly benefit from arrays of receivers.

TABLE 3

SMIM/FIRST TECHNOLOGY FUNDING REQUIREMENTS
RECEIVER DEVELOPMENT

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
A. SIS Receiver Systems	400	420	441	463	486
B. Focal Plane Mixer Array Development	400	420	441	463	486
TOTAL	800	840	882	926	972

A. SIS Receiver System

A.1 OBJECTIVE: The objective of this program element will be to optimize the mixer mounts to provide performance closer to the needs of the SMIM/FIRST instruments. In particular, the mounts will be optimized for 10% bandwidth, and a broad bandwidth IF from 8 to 12 GHz. In addition, optimization of either single-sideband or double-sideband operation will be addressed.

A.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

A.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	1. Receivers to 600 GHz	-receivers with T_{rx} <10 hν/k for ν<500 GHz -receivers with T_{rx} = 80 hν/k for 630 GHz	-receivers with T_{rx} < 20 hν/k -10% fixed tuned band width - 8-12 GHz IF	9/95
	2. Receivers to 800 GHz		-receivers with T_{rx} < 20 hν/k -10% fixed tuned band width - 8-12 GHz IF	9/97
	3. Receivers to 1200 GHz		-receivers with T_{rx} < 20 hν/k -10% fixed tuned band width - 8-12 GHz IF	9/98

(T_{rx} =receiver temperature)

A.4 PAYOFF / PERFORMANCE

T_{rx} < 20 hν/k -> currently meet requirement below 500 GHz, to enable SMIM/FIRST to reach 1200 GHz

Increased frequency -> access to important spectral features between 500 and 1200 GHz

10% bandwidth -> broad instantaneous bandwidth; allows access to larger frequency range with fewer number of receivers; saves cost

8-12 GHz IF -> the wider the IF bandwidth, the greater the number of spectral channels that can be observed simultaneously; reducing observing time for a given spectral range and sensitivity

A.5 EXISTING EFFORTS: OSSA Planetary Astronomy program; OSSA Astrophysics program at JPL; OSSA Astrophysics program at Caltech

A.6 ISSUES: An appropriate RF imbedding impedance must be provided to the tunnel junction to optimize mixer performance over a 10% bandwidth. RF losses in fixed-tuned planar and waveguide circuits need to be minimized. Novel geometries of multi-section transformers and tuners need to be investigated. The relative sideband performance must be evaluated. Tradeoff in overall performance between single- and double-sideband operation is needed. Mixer architectures need to be developed for both single- and double-sideband operation.

B. Focal Plane Mixer Array Development

B.1 OBJECTIVES: The objective of this task is to develop a focal plane array capability for submillimeter wave heterodyne receivers. Focal plane arrays greatly enhance the data taking capability in a given period of time. Further, observing runs which are of limited duration such as from aircraft or balloon platforms will greatly benefit from arrays of receivers.

B.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

B.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	- Small element arrays - Planar approach preferred up to 2000 GHz	T_{rx}=250 K over 10 elements at 230 GHz	$T_{rx} < 0.7\ \sqrt{n}\ T_{rx}$ of single element receivers at the same frequency	2006

(T_{rx} =receiver temperature)

B.4 PAYOFF / PERFORMANCE

small element array -> enhance data-taking throughput

B.5 EXISTING EFFORTS: NASA OAST program at JPL, NSF program at Caltech

B.6 ISSUES The issues to be addressed are (1) the development of efficient, low-loss antenna-coupling structures suitable for array applications; (2) the development of efficient, uniform, LO-illumination techniques; (3) the development of multi-beam optical systems with near-diffraction-limited coupling and overlap at the half-power point on the sky; (4) the development of array test and characterization techniques to measure beam efficiency and position, mutual coupling, junction performance, LO coupling; and (6) the development of efficient IF removal schemes for a large number of array elements.

4.0 Intermediate Frequency Amplifier Development

The first amplifier in the intermediate frequency chain must not contribute more than 10% of the total receiver noise. A mixer conversion loss of 10 dB implies a noise temperature of ~5 - 10 K. The gain must be enough so that subsequent amplifiers will not contribute significantly to the receiver noise. The IF frequency is from 8 to 12 GHz. Since the first IF amplifier is located in the cryostat at 2 K, it must dissipate very low amounts of power. It's power dissipation dominates the heat load from the instrument in the dewar.

TABLE 4

SMIM/FIRST TECHNOLOGY FUNDING REQUIREMENTS
IF AMPLIFIER DEVELOPMENT

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
A. IF Amplifier Development*	300	315	331	347	365
TOTAL	300	315	331	347	365

*Not funded under ITP Plan

A. Low-Power Cryogenic IF Amplifier Development

A.1 OBJECTIVE: The objective is to develop an 8 - 12 GHz IF amplifier with a noise temperature of < 10 K, which dissipates < 5 mW at the 2K stage of cryostat.

A.2 APPLICATIONS / MISSIONS ENABLED: SMIM/FIRST, LDR, SALSA

A.3	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
	HEMT amplifier	- 8-12 GHz available - noise temp 10K - power dissipation 10 to 15 mW	- 8-12 GHz available - noise temp 10K - power dissipation 5 mW	9/96

A.4 PAYOFF / PERFORMANCE

Band width -> the greater the bandwidth, the greater the multiplexing advantage

low power dissipation -> the first IF amplifier is the primary power input to the dewar; the lower the power, the longer the mission

A.5 EXISTING EFFORTS: none

A.6 ISSUES: The primary issue is reducing the power dissipation at 2K while maintaining performance.

5.0 Innovative Approaches to Submillimeter Wave Sensors

The Astrotech 21 Submillimeter Wave Advisory Group indicated a need to explore new and innovative approaches to both mixer and LO development. There is a strong astrophysics submillimeter-wave technology-development community in universities. In addition, valuable expertise is available in government laboratories. The commercial market in this area is small, but several companies may contribute to the program. One of the goals of this program is to solicit national input on innovative approaches to submillimeter-wave sensors through an NRA process. The review and selection criteria for this part of the program will be developed based on discussion with NASA headquarters, the Submillimeter Wave Science Working Group, and SMIM/FIRST study management.

TABLE 5

SMIM/FIRST TECHNOLOGY FUNDING REQUIREMENTS
INNOVATIVE APPROACHES TO SUBMILLIMETER SENSORS

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
A. New Concepts for Detection at Submm	300	315	331	347	365
B. New Concepts for Submm	300	315	331	347	365
C. New Superconducting Materials for Submm Applications	250	263	276	289	304
D. New Semiconducting Materials for Submm Applications	250	263	276	289	304
E. New Circuit and Coupling Concepts	250	263	276	289	304
F. Array Detection Concepts	250	263	276	289	304
TOTAL	1600	1680	1764	1852	194[illegible]

A. New Concepts for Detection at Submillimeter Wavelengths

New and innovative concepts for heterodyne detection in the submillimeter wave range will be solicited. Mixers are currently based on device nonlinear I-V characteristics. SIS tunnel junctions at millimeter wavelengths have demonstrated near-theoretical performance, and are the baseline for future astrophysics missions, but have not been demonstrated above 600 GHz. Alternative mixer devices based on the non-linear I-V characteristic include superconducting-insulator-normal metal (SIN) junctions, planar GaAs Schottky diodes, and new versions of photo conductors. These, and other as yet undetermined devices, are possible candidates. In addition, concepts exploiting other types of nonlinearity will be considered.

B. New Concepts for Submillimeter Wave Local Oscillators

New and innovative concepts for local oscillators in the submillimeter wave range will be requested. Currently defined NASA submillimeter wave missions use as a baseline multiplied LO sources because the power provided by fundamental oscillators is at least an order of magnitude lower than required at submillimeter wavelengths. However, a solid-state fundamental oscillator operating in the submillimeter wavelength range is a very attractive long-term approach, because it is inherently more efficient and less complex than a multiplied source. Some alternatives for fundamental oscillators include quantum-well oscillators, Josephson-junction oscillators, and optically switched oscillators. Many of these oscillators appear to be inherently low-power sources; thus, it is necessary to develop methods for power combining in order to generate adequate power to drive the mixers. These, and other as yet undetermined approaches, would be considered in response to a call for proposal.

C. New Superconducting Materials for Submillimeter Wave Applications

New superconductor-insulator material systems with larger superconducting energy gaps, high speed, and lower RF losses are needed for the higher frequency regime. New techniques for improving thin-film growth and improved superconductor-insulator interfaces are critical for device fabrication. In addition, innovative device architectures and approaches to processing which could improve device performance would be explored under this task.

D. New Semiconducting Materials for Submillimeter Wave Applications

Novel semiconductor-material systems that provide better high-frequency device performance would be developed under this task. Developing approaches to reduce inherent frequency limitations associated with transport mechanisms, such as using higher mobility materials or two-dimensional electron gases, might fall in this category. In addition, a study of barrier materials to increase barrier height and reduce losses is required for device development. Novel processing techniques leading to new device geometries employing semiconductors would also be included in this task.

E. New Circuit and Coupling Concepts

Innovative approaches to circuit architectures and coupling techniques will be solicited. Research areas include the development of transmission-line approaches, such as micro-machined waveguide, dielectric waveguide, or quasi-optical components. This could also include mixer circuits using multiple mixer diodes for improved mixer performance, such as balanced mixers, crossbar mixers, and subharmonic mixers, or grid mixers. The circuits could be implemented in a variety of transmission lines. For local oscillators, in addition to novel circuit implementations, techniques for power combining would be a possible candidate.

F. Array Detection Concepts

In a given time interval, data acquisition can be greatly enhanced by the use of focal plane arrays. Arrays of receivers would be of considerable benefit during observing runs of limited duration, such as those carried out from aircraft or balloon platforms. LDR has array receivers as its baseline. To date, arrays at millimeter wavelengths have been implemented by packing waveguide mixer feedhorns as closely as possible. This approach becomes less practical at shorter submillimeter wavelengths. Other approaches might employ planar antenna arrays, or use micromachining to fabricate feedhorn arrays. Such an approach might also include concepts for novel low-noise preamplifier arrays with low bias power levels. This program element would support research groups developing different approaches to array receivers.

6.0. Technology Transfer to the Commercial Sector

Technology being developed for SMIM/FIRST with potential commercial applications includes LO sources and mixers:

1) LO sources consist of three components, each of which can be used separately:
- a) Millimeter-wave pump sources with
  - i) output frequencies in range 60 to 120 GHz
  - ii) >100 mW output power
  - iii) 10% electrically tuned bandwidth
  - iv) 1:10^6 spectral purity
- b) Intermediate multipliers
  - i) output frequencies in range 160 to 360 GHz
  - ii) >5 mW output power
  - iii) 10% fixed tuned bandwidth
- c) High frequency multipliers
  - 1) output frequency in range 400 to 1200 GHz
  - ii) >50 μW output power
  - iii) 10% fixed tuned bandwidth.

2) The mixers using superconducting non-linear elements employ several types of circuit architectures:
- i) Waveguide
- ii) Planar antennas
- iii) Planar focal plane arrays.

The near-term technology transfer potential for these technologies includes:
1) Frequency-agile laboratory sources
2) Frequency transmitter and receiver for antenna ranges
3) Driver for submillimeter radar cross section modeling systems
4) Submillimeter materials measurement systems
5) Submillimeter imaging systems.

Longer term, more generic spin-offs include:
1) New low-loss planar circuit topologies
2) Three-dimensional circuit topologies using micromachining technology
3) Planar device architectures with very low parasitic losses.

7.0 Summary of Submillimeter Heterodyne Receiver Technology Needs

A. Priorities

Highest Priority
- Superconducting Mixers
- Solid State Local Oscillators
- Receivers
- Innovative Research

Higher Priority
- IF Amplifier Development

B. Overall Funding

TABLE 6

SIS HETERODYNE RECEIVER TECHNOLOGY

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97
1. Superconducting Mixer Development	1550	1628	1709	1794	1884
2. Solid State Local Oscillator Development	1350	1418	1488	1563	1641
3. Receiver Development	800	840	882	926	972
4. IF Amplifier Development	300	315	331	347	365
5. Innovative Research (NRA)	1600	1680	1764	1852	1945
TOTAL	5600	5880	6174	6483	6807

IV. TELESCOPE TECHNOLOGY

The SMIM/FIRST mission requires a 2.5-4.5 meter diameter, lightweight, parabolic primary reflector. While monolithic design concepts exist for this reflector, it is highly probable that it will be segmented. The individual segments will be "pie" shaped, off-axis, parabolic panels of ≈1-1.25 meters in size (or larger, if a 1-ring, 4.5 meter design is adopted). The panels will be fabricated from advanced composite materials, and must achieve figure errors of <3-6 microns rms on orbit at a temperature of ≈100-150K (depending on orbit). The allowable variation in the focal length of individual panels is ±0.25 mm. Advanced materials and innovative technology developed in an alliance between NASA and U.S. industry, as part of the Precision Segmented Reflector program funded by NASA-OACT, has given U.S. industry the technological lead in the development of lightweight, thermally stable, precision composite panels for submillimeter space telescope applications.

Current state-of-the-art panels are spherical (3.25 and 1.5 meters focal length), 1.0 meter in size, hexagonal in shape and are fabricated from new, advanced graphite/cyanate ester composite materials. Figure errors are routinely in the range of 1-5 microns rms for 1 meter size panels at 150-180K. The variation in the focal length among panels of the same design and construction has not been adequately investigated. It is believed, however, to be in the range of ±2.5 mm, based on limited studies. The repeatable fabrication of off-axis, parabolic panels of 1-1.25 meter size and the appropriate geometry must be demonstrated. The development of better manufacturing techniques or post-fabrication finishing techniques may be required to reduce the variation in focal length to an acceptable level.

In order to achieve panel technology readiness for a SMIM/FIRST start, possibly as early as 1997, it will be necessary for NASA to expand its alliance with U.S. industry and take advantage of our lead in the panel technology area to achieve the demanding mission requirements in a timely manner. Furthermore, U.S. industry can use the innovative technology, advanced materials and precision composite manufacturing techniques resulting from this alliance to improve performance and reduce cost of products for space and terrestrial applications, including high-frequency communication antennas, optical benches and advanced tactical and commercial aircraft, thus increasing our competitiveness in the world market.

In addition to the panel technology development, a comprehensive systems-engineering effort is required in order to develop credible, cost-effective designs for the SMIM/FIRST segments, reflector and telescope, and to demonstrate integration of panels and related hardware/systems in a suitable testbed, in order to validate the performance of the SMIM/FIRST telescope in a space-like environment. Several competing concepts have been proposed which must be further defined, evaluated and demonstrated to be feasible prior to their adoption. The issues to be addressed include: segment geometry, panel support structure design, panel/structure interface hardware, panel alignment and phasing, passive vs. active control of the panels and the structure, and the integration of optics, panels, structure, and alignment and control systems. The systems-engineering effort will include: (1) a feasibility/risk assessment and trade study of the competing concepts for the panel support structure (passive optical bench vs. actively controlled lightweight truss); (2) a feasibility/risk assessment and trade study of the competing concepts for panel alignment and control (ground alignment/no in-space control vs. in-space alignment/active control); (3) demonstration of integration of panels and key panel related components and systems on existing Phase 1 telescope testbed; and (4) demonstration of SMIM/FIRST design concepts in a fully integrated Phase 2 SMIM/FIRST-like testbed at operational temperature.

The SMIM/FIRST systems-engineering effort will assess and develop design concepts which have applicability beyond submillimeter space telescopes. The panel and structure design studies will be applicable to both space-based and terrestrial optical communications receivers operating in a light-bucket mode with segmented composite collectors. The analysis of the panel and structure control system requirements will have applicability to the design and operation of a variety of complex multi-variable systems. Finally, the testbeds, developed as part of the systemsengineering effort will be available to NASA, the U.S. government, and U.S. industry for evaluation of innovative and advanced optics and telescope technology.

To achieve these ambitious goals in a timely manner necessary to meet a near-term SMIM/FIRST mission technology readiness date, an ambitious joint effort on the part of NASA and U.S. industry is required. The development of the panels and the definition/demonstration of related reflector and telescope design concepts, systems and hardware needs to be closely related.

A. Composite Panel Development

A.1 OBJECTIVE: The objective of this task is to develop and demonstrate composite mirror panel technology for the SMIM/FIRST primary mirror.

A.2 APPLICATIONS/MISSIONS ENABLED: SMIM/FIRST, IRST-NG, SALSA , LDR

A.3

	REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
1.	Materials and coatings for lightweight, precision, thermally stable, environmentally stable reflector panels	Facesheets- graphite cyanate laminates, preliminary characterization complete; Core- graphite epoxy, 5 ppm CTE, 5% H_2O absorption; Coatings- existing coatings primarily for visible and near IR	Facesheets- space qualified advanced composite laminates; Core- advanced composite, <1 ppm CTE, 1% H_2O absorption; Coatings- 99% reflectivity for 30-1000 µm, < 0.5% emissivity for λ>30 µm, high emissivity for λ<30 µm	10/96
2.	Cryogenic test facility	Handles 1.47 m, spherical pieces to 150K; measures focal length to < 50 µm	Handle 1.25m, off-axis parabolic pieces to 100K; measure focal length to <50 µm	1/95
3.	Lightweight, precision, thermally stable, environmentally stable reflector panels	1.0 m size, hexagonal, spherical, 1.5 m focal length, 5-10 kg/m^2, 1-5 microns rms figure at 150K, ≈2.5 mm variation in focal length from panel to panel	1.0-1.25 m size, pie shaped, off-axis parabolic, 1.5 m focal length, 5-7 kg/m^2, 3-6 microns rms figure at 100K, 0.25 mm variation in focal length from panel to panel	10/97

A.4 PAYOFF/PERFORMANCE:

- Lightweight: enables large apertures; launch vehicles are mass constrained; enables lightweight chopping mirrors; could enhance several near-term EOS missions (EOS-MLS, LAWS); could enhance planetary missions by providing smaller, lighter high-gain antennas (Pluto Fast-Flyby)
- Precision: enables far-IR and submillimeter space telescopes; could enable optical communication antennas operating in the light-bucket mode (Deep Space Relay Satellite, Deep Space Optical Reception Antenna)
- Stability: enables long-term missions without the need for deformable panels to maintain figure
- Panel fabrication hardware (molds, etc.) will be available for SMIM/FIRST flight hardware fabrication thus reducing mission costs
- U.S. industry can utilize the innovative technology, advanced materials and precision composite manufacturing techniques resulting from this alliance to improve performance and reduce cost of products for space and terrestrial applications thus increasing their competitiveness in the world market.

A.5 EXISTING EFFORTS:

OACT sponsored Precision Segmented Reflector/Telescope Technology (PSR/TT) program was the only effort in the U.S. addressing lightweight, precision, high stability, composite reflector technology

A.6 ISSUES:

The PSR/TT program has not been funded beyond 1992

B. Systems Engineering

B.1 OBJECTIVE: The objective of this task is to evaluate feasibility and risk, and perform system trades for SMIM/FIRST telescope design concepts; to evaluate interplay between panel thermal design, optical design and control system requirements; and to demonstrate integration of panels and related hardware/systems in a telescope testbed to validate their performance as part of a SMIM/FIRST telescope in a space-like environment.

B.2 APPLICATIONS/MISSIONS ENABLED: SMIM/FIRST, IRST-NG, SALSA, LDR

B.3

REQUIRED TECHNOLOGY	CURRENT SOA	REQUIREMENT	DATE
1. Integrated Testbeds	2.3 meter, spherical, aluminum, room temperature, two panel testbed exists; no tests performed due to lack of PSR/TT funding	Verify panel mounting, alignment and phasing with Phase 1 integrated system; validate SMIM/FIRST design concept with Phase 2 testbed- 2.5 m minimum size, parabolic, composite structure, appropriate panel number, size and geometry, 100K operation	Phase 1- 10/96 Phase 2- 10/98

B.4 PAYOFF/PERFORMANCE:

- Panels: demonstrate that panel figure, focal length variation and stability meet requirements for aligning, phasing and operating telescope
- Mounts: demonstrate that panel/structure interface designs meet mission requirements
- Structure: assess competing structure concepts (passive optical bench vs. actively controlled lightweight truss), select and validate approach to meet SMIM/FIRST requirements
- Controls: assess competing alignment/figure control concepts (ground alignment/no in-space control vs. in-space alignment/active control), select and validate approach to meet SMIM/FIRST requirements
- Testbed will be available for future SMIM/FIRST flight hardware development needs
- Design studies and testbed demonstrations will provide industry with technology applicable to both space based and terrestrial precision composite structures (antennas, optical benches, truss structures, aircraft)
- Testbed will be available for evaluation of innovative technology developed by NASA, U.S. government and U.S. industry

B.5 EXISTING EFFORTS:

Concept development on-going by SMIM/FIRST; Phase 1 testbed built by PSR/TT, but not operational due to lack of funding.

B.6 ISSUES: The PSR/TT program has not been funded beyond 1992

TABLE 7

SMIM/FIRST TELESCOPE TECHNOLOGY BUDGET ($K)

Activity	FY93	FY94	FY95	FY96	FY97	FY98	TOTAL
Composite Panel Development							
Panel Development	500	1900	2100	1700	1700	0	7900
System Engineering							
Phase 1 Testbed	100	300	300	200	0	0	900
Telescope Structure Study	0	200	200	0	0	0	400
Telescope Controls Study	100	200	200	0	0	0	500
Phase 2 SMIM/FIRST-like Testbed	0	100	900	1400	1000	800	4200
TOTALS	700	2700	3700	3300	2700	800	13900

V. PROJECT MANAGEMENT

The management responsibility for the technology development tasks described in this plan will rest with a Study/Project Technologist, who will also be the Deputy Study/Project Manager and report to the Study/Project Manager. The Study/Project Technologist resides at the NASA center that has overall responsibility for the project.

As part of his or her responsibilities, the Study/Project Technologist will ensure that the technology development is technically sound, up-to-date, and within acceptable risk and cost, and that it meets the project's system engineering and integration requirements.

The goal of the technology development tasks is to determine and demonstrate the best possible technical solutions to the project's engineering and technical challenges. To achieve this goal, participation will be solicited from interested and capable parties at universities, in industry, and at Federal laboratories, including NASA centers. Consideration will be given to proposals ranging from traditional approaches, requiring only minor extensions beyond current technical capabilities, to radical approaches for solving the project's engineering and technical challenges.

It is anticipated that initially, for each task, parallel paths will be pursued in solving the challenges; and that, in each case, from those paths the best solution will be down-selected for final development and demonstration. Clear descriptions of these parallel paths, including milestones and decision points, as well as adherence to the schedule, will be required. Teaming arrangements, possibly involving universities, industry, NASA centers, and other Federal laboratories, will be strongly encouraged.

VI. SUMMARY

While all of the above discussed technologies are critical to enabling a SMIM/FIRST new start before the end of the decade, some are more critical than others. Table 8 shows priorities for the technologies discussed in this plan. The technologies are grouped into three classifications: the highest priority, higher priority, and high priority. The rankings are similar to previous priorities provided to OACT. Lower ranked technologies, while critical, were either more mature, or their development could begin later. The major exception is the overall Telescope Technology program, where funding is not now allocated for FY93 or FY94. Without OACT funding, the light-weight, low-cost composite panel development will come to a halt, even though the cost and performance benefits are both significant and enabling, not only for SMIM/FIRST but for a whole generation of new space telescopes, including IRST-NG and SALSA.

TABLE 8

SMIM/FIRST TECHNOLOGY PRIORITIZATION

Highest Priority

Superconducting Mixers
Solid State Local Oscillators
SIS Heterodyne Receivers
Composite Panel Development

Higher Priority

Innovative SIS Research
Telescope Systems Engineering

High Priority

IF Amplifier Development

TABLE 9

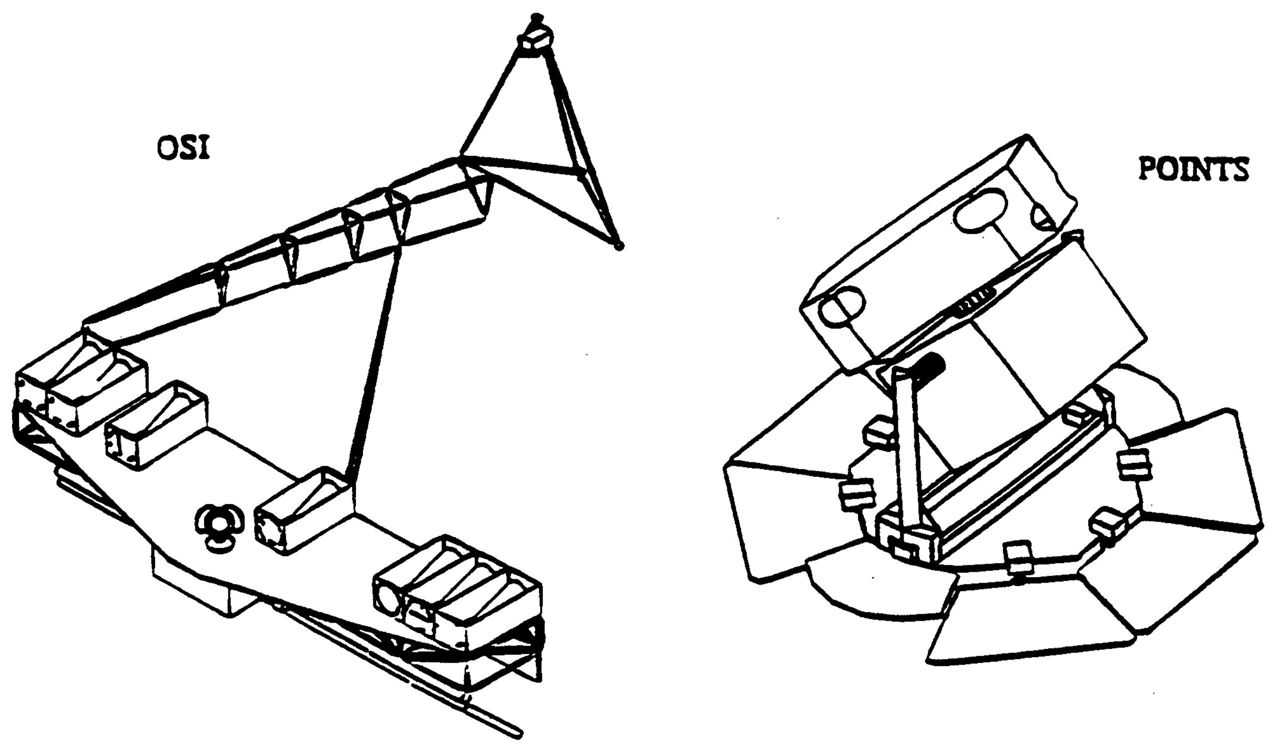
SMIM/FIRST TECHNOLOGY FUNDING SUMMARY

OACT FUNDING	FY93	FY94	FY95	FY96	FY97	FY98
SIS Heterodyne Development ITP	$5600K	$5880K	$6174K	$6483K	$6807K	--
Telescope Technology	$700K	$2700K	$3700K	$3300K	$2700K	$800K
TOTAL	$6300K	$8580K	$9874K	$9783K	$9507K	$800K

AIM

Astrometric Interferometry Mission

Technology Plan



March 19, 1993

Director, Space Science and Operations Division
Office of Advanced Concepts and Technology
NASA Headquarters

Michael S. Kaplan
Chief, Advanced Programs Branch
Astrophysics Division
Office of Space Science and Applications

AIM

Study Manager:	Mike Kaplan, NASA HQs
Study Scientist:	Bob Stachnik, NASA HQs
Study Manager:	Marc Rayman, JPL
Project Technologist:	Bob Laskin, JPL
Project Scientist:	Mike Shao, JPL

3/19/93

Table of Contents

I. INTRODUCTION

The purpose of this plan is to provide OACT with the near-term technology needs for the Astrometric Interferometry Mission (AIM). To ensure that AIM can begin phase C/D in 1999, Advanced Technology Development (ATD) must be completed within the next 5-7 years.

AIM will be a space-based optical interferometer that will achieve unprecedented accuracy in the measurement of stellar positions throughout our galaxy, and beyond. AIM will measure the positions of stars, quasars, and distant galaxies with an accuracy of 3-30 microarcseconds—an improvement of two to three orders of magnitude over existing astrometric data—and will help calibrate the cosmic distance scale. AIM will also investigate galactic and solar system structure and evolution, and may detect planets outside the solar system.

Following SIRTF and SMIM, AIM is the highest priority new program in the Astrophysics Division, and is scheduled for a new start around FY99. AIM was recommended for Pre-Phase A study by the National Research Council's Astronomy and Astrophysics Survey Committee and was endorsed by the Space Science and Applications Advisory Committee.

AIM-related requirements in the highest priority of the OSSA Technology Needs matrix include "Interferometer-Specific Technology," consisting of picometer metrology, active delay lines, and control-structures interactions (CSI). Also in OSSA's highest priority category are "Vibration Isolation Technology," "Lasers: Long-life, Stable & Tunable," and "Precision Sensing, Pointing & Control," all of vital importance to space-based optical interferometry systems. In support of AIM, OACT (formerly OAST) is funding the Micro-Precision CSI program at the Jet Propulsion Laboratory (JPL); however, this funding is barely sufficient to keep the program alive at present, and far below the level of funding required to develop the interferometer technology for an AIM new start in this century.

Astrotech 21, a joint program between OAST (now OACT) and the OSSA Astrophysics Division, was initiated in 1989 to develop technologies for future Astrophysics missions in the 1995-2015 timeframe. Astrotech 21 held two interferometry workshops that studied the science objectives, architectures, and technologies for optical interferometry in space (see Astrotech 21 Workshop Series I, volume 1, and Series II, volume 1). The results of these workshops form the basis of this technology plan.

There are two AIM candidate missions, the Orbiting Stellar Interferometer (OSI) and the Precision Optical Interferometer in Space (POINTS), both described in detail in the Astrotech 21 documents. In its current configuration, OSI is a 7-meter-baseline interferometer with seven 0.33-m apertures, and has the capability for both astrometry and imaging. POINTS is an astrometric interferometer with a 2-m baseline consisting of two pairs of 0.25-m diameter apertures. Since OSI and POINTS differ in scope and structure, their technology requirements will be considered separately in this plan.

The Space Interferometry Science Working Group (SISWG) was established by the Astrophysics Division in early 1992 to define program goals for AIM, to assess the science and technology requirements for achieving those goals, and to recommend a specific mission architecture in 1993 or 1994. Their assessment will affect AIM technology requirements.

OSSA's Solar System Exploration Division has a similar study for its Toward Other Planetary Systems (TOPS-1) mission. Three candidate missions, including OSI and POINTS, are under consideration by the TOPS Science Working Group, who will render their decision at approximately the same time as the SISWG. Currently, OSSA funds technology development for OSI through the Astrophysics Division; POINTS is funded through the Solar System Exploration Division.

II. ADVANCED TECHNOLOGY DEVELOPMENT FUNDING: BACKGROUND HISTORY AND PROJECTED REQUIREMENTS

Some of the technologies discussed below are applicable to a wide variety of space missions other than AIM. These technologies include active and passive damping, vibration isolation, and the development of detectors, lasers, wide-band spectrometers, beam distribution systems, and analysis tools. Some, such as picometer metrology, push beyond the current state of the art. Challenges such as ultra-precision deployment and operation of active delay lines under zero-g conditions, are likely to be faced by larger, more complex interferometers and "floppy structures" in future missions; mission studies and technology development for AIM can serve as a testbed for possible solutions to these problems.

A. OSI

The OSI group at JPL received about $250k per year in FY91 and FY92 from the Astrophysics Division. Code R provided the OSI group with about

$100k/year during FY91 and FY92 to identify new technology requirements, both for OSI and for possible future interferometry missions. In addition, individual members of the OSI group have contributed to the CSI program. An OSIlike structural model developed for CSI was jointly funded by the Astrophysics Division and OAST/OACT for about $10k-20k each. Under OAST/OACT's Telescope Optical Systems (TOS) Plan, which is contingent on a $100M augmentation of OAST's budget, OSI would receive $200k-$300k annually in FY93 and FY94. Such an augmentation is very unlikely.

The CSI program, funded by OAST at $4.5M in FY92, studies structures that resemble AIM candidate spacecraft. To date, CSI has performed measurements on an OSI-like structure at JPL. No POINTS-like structure has been examined; such a model is, however, included in FY93 plans.

OSI will require around $6M annually for technology development through phase B (phase C/D is scheduled to begin in 1999; details in section V.A), in addition to about $3.5M-$4.5M annually (FY93-FY97) for CSI. Principal annual funding requirements (besides CSI) include about $3M for metrology, $2M for active delay lines, and $1M for development of precision deployable structures.

OSI metrology development goals include relative metrology to 25 picometer (pm) accuracy, measurement of 3-D motion of optical fiducials to 200-250 pm accuracy, and measurement of 1-D absolute distance to 10 μm. Active delay lines have already been developed by members of the OSI group for an operational ground-based optical interferometer (the Mark III on Mt. Wilson), but must be adapted for use in zero-g. Passive damping studies, funded under the CSI program, will include testing existing passive damping structures, such as the isolation of reaction wheels in the Hubble Space Telescope (HST), as applied to OSI. The combination of active delay lines and passive damping needs to achieve control of optical paths to 10 nm.

B. POINTS

The POINTS group (at Harvard-Smithsonian Astrophysical Observatory (SAO), with JPL support) received about $400k to date from the Solar System Exploration Division, but no funding from either OAST/OACT or Astrophysics Division. Advanced technology development (ATD) costs for POINTS through Phase B will average around $9M annually (FY93-FY97), including about $2.6M-$3.6M/year for CSI. CSI funding will cover studies and technology development for vibration isolation, and development of the instrument fine-pointing system. The principal requirement besides CSI will be about \$2M-\$5M per year for metrology. Additional funding (\$0.5M-\$1.0M/year) will be needed to improve detectors for wide-band spectrometers, around \$2M total funding for development and testing of low CTE [Coefficient of Thermal Expansion] materials, and another \$2M total for design and evaluation of optical benches.

Metrology development will focus on opto-electronic components, null and incremental laser gauges, optically contacted endpoint assemblies and their precision alignment, beam distribution techniques, and starlight beam splitters. The SAO group is actively engaged in developing laser gauges for picometer metrology. Continuation of recent developments at JPL in δ-doped CCDs for ultraviolet, visible, and near-infrared (to ~1 μm) wavelengths may significantly enhance POINTS's detection capability.

III. ORGANIZATION OF THE PLAN

The plan is organized around six technology development areas in order of their priority. Some of these areas are appropriate to only one of the two candidate missions, and are so designated; others are common to both OSI and POINTS. For each technology area, the following information is provided: Title, Objective, Mission Enabled, Required Technology, Payoff/Performance, Existing Efforts, and Issues. Following the discussion of these technology areas, a major milestone schedule and funding requirements are given. In the concluding section for this plan, technology development priorities are reviewed.

IV. INTERFEROMETER TECHNOLOGY NEEDS

AIM is the prototype for future mission concepts that employ more than one aperture. Baselines [between apertures] may be up to 30 meters in extent in space and hundreds of meters on the moon. High precision metrology requirements, within an element and between elements of an interferometer, are AIM's driving technology requirement.

OSI technology development needs, in order of priority, are as follows:

- Metrology
- Active Delay Lines
- Disturbance Isolation
- Quiet Structures and Subsystems, Precision Deployment
- Thermally Stable Optical Elements

POINTS technology development needs, in order of priority, are as follows:

- Metrology
- Fine Pointing with Isolation
- Materials and Structures for Stiff Optical Instruments
- Thermally Stable Optical Elements
- Quiet Spacecraft (S/C) Subsystems

A. METROLOGY

- Objective:

  Measurement of distances to sub-nanometer accuracies. Range of distances is from 1 to 10 m.

- Mission Enabled:

  OSI, POINTS

• Required Technology:

Technology	Current State of the Art	Science Mission Requirement	Date Needed
Stabilized Lasers	• Suitable lasers working in lab • Stabilized HeNe lasers commercially avail. ~100x more stable than req.	1 part in 10^{10}	'97
Laser gauges	• Commercial units insufficient • Some technology working in lab	Picometer accuracy	'97
Components for Laser gauges: Modulators, Optical Fibers, Beam-splitters, Integrated Optics	Devices exist but not in space-worthy form	TBD	'97
Tunable Lasers for Absolute Laser gauging	Concept only	300 GHz tuning range; 1 part in 10 accuracy of frequency markers	'97
End-points (mechanical assemblies of optical components)	Concepts developed	μm alignment of parts to be optically contacted or joined in other very stable way	'97
Holographic Optical Elements (HOE) (POINTS only)	• Concepts developed for metrology • Manufactured by industry for other applications	Uniform diffractive efficiency to 1%	'97

• Payoff / Performance:

Precise distance determination, which is necessary to convert the precision of an interferometer into accuracy; can be used as a sensor for CSI systems and for precision terrestrial systems, e.g., microscopes (atomic force; scanning; tunneling), nano-g accelerometers & other "nanotechnology", and solid memory (molecular)

- Existing Efforts:

  Laser gauges are being developed at SAO (POINTS) and JPL (OSI).

- Issues:

  Need for absolute distance gauges (cf., incremental gauges like the HP laser gauge)

B. FINE POINTING WITH ISOLATION

- Objective:

  Reduce need for high bandwidth optical compensation (not practical with photon-starved optical sensors)

- Mission Enabled/Enhanced:

  POINTS

• Required Technology:

Technology	Current State of the Art	Science Mission Requirement	Date Needed
Inertial Reference	RMS noise in a band from 0.1 to 100 Hz • Gyros with field history: 3.5 mas • Gyros tested in lab: 0.7 mas • Angular displacement sensor: TBD (good performance above 1 Hz)	Better than 1 mas rms over 0.1 -100 Hz band	'97
Six-degree Suspension for Vibration Isolation plus Fine Pointing	Concept developed (e.g., by HDOS* for SIRTF secondary mirror, rigid support; HST reaction-wheel passive isolator: single-axis prototype active system demonstrated by CSI in lab)	Increase isolation by x50 over HST; demo on flight like testbed; use force transducers, not displacement transducers	'97

**HDOS = Hughes Danbury Optical Systems*

• Payoff / Performance:

Fringes can be made stable on an integrating detector; reduced detector read noise; reduced computational burden.

Effective isolation of fine-pointing suspension reduces need for other isolation of mechanically noisy components, e.g., reaction wheels.

The addition of a fine-pointing system eases the requirements of both the pointing gimbals and the S/C attitude control system.

• Existing Efforts:

Honeywell Magnetic Suspension -- very high cost, mass, power. JPL CSI Program's Active/Passive Hybrid Concept -- x10 rms isolation achieved on preliminary single-axis system. Major effort at JPL to begin October 1992, if funding is provided.

- Issues:

For bright objects, fringes can be tracked in software (S/W) with fast-read detectors. Astrometric information can be extracted from the fringe-tracking and metrology filter. For dim objects, high bandwidth optical compensation is not possible; isolation can reduce fringe jitter.

C ACTIVE DELAY LINES

- Objective:

Equalize path lengths of interferometer arms; suppress optical effects of structural vibrations.

- Mission Enabled:

OSI

- Required Technology:

Technology	**Current State of the Art**	**Science Mission Requirement**	**Date Needed**
Moving Carriage with Retroflector	Designs for ground-based interferometers	Lightweight, balanced actuators, low induced structural vibrations, 10 nm rms jitter	'97
OPD* Monitoring	(see metrology)	(see metrology)	'97
Vibration Suppression	Heavy carriage system achieved ~10 nm rms jitter on small-scale CSI testbed	Suppress structural vibrations to < 10 nm rms	'97

*OPD = Optical Path Distance

- Payoff / Performance:

Required in order to make fringes in a class of interferometers.

Rapid precision delay lines permit quick re-targetting and correspondingly high number of measurements per day.

- Existing Efforts:

Ground-based interferometers in use and under development:
- JPL/USNO [US Naval Observatory]/SAO et al.
- Infrared delay lines for space-based FTS.
- Heavy delay lines tested on small-scale CSI truss structure testbed.

- Issues:

None.

D. QUIET STRUCTURES AND SUBSYSTEMS, PRECISION DEPLOYMENT

- Objective:

Develop and verify methods of designing structures and mechanical control systems that are stable, highly linear, and have a low level of mechanical noise. Develop S/W capable of high-fidelity modeling and optimization of structure/control/optics/thermal systems in order to achieve precise post-launch deployment and quiet operation. Develop quiet S/C subsystems: attitude control actuators, solar array drives, etc.

- Mission Enabled:

OSI, POINTS

- Payoff / Performance:

  - Fringes visible only if vibration of OPD is small compared to an optical wavelength. Quiet structures reduce the control requirement of optical feedback loops.
  - Reliable determination of fringe visibility, as required for interferometric imaging, requires vibration of OPD to be very small compared to an optical wavelength.

- Higher ratio of performance to mass for structures: lower cost for large, high-performance structures.
- Ability to accurately predict end-to-end system performance prior to build

- Existing Efforts:

  NASA Micro-Precision CSI program.

- Issues:

  None.

• Required Technology:

Technology	Current State of the Art	Science Mission Requirement	Date Needed
Microdynamics of Structures	Preliminary investigations	Accurate modeling and extensive data-base of structures at nanometer levels	'97
Passive Damping, esp. at low amplitude	Passive struts for reaction wheel isolation on HST; CSI D-struts** bench tested to 15 nm	Struts to provide x20 damping over flight temperatures	'97
Active Damping	CSI active members demonstrated on small-scale testbed	Provide x20 damping; stiff at low freq; stroke suff. for 1 mm on-orbit alignment correction	'97
Low-Cost Vibration Isolation	Passive: x3 suppression for HST reaction-wheel isolators. Active: magnetic isolators -- risky, bulky, expensive	x100 suppression	'97
CSI Integrated Modeling & Design	"Alpha" S/W	Proven S/W for hi fi modeling & mass optimization design	'97
Deployable Precision Structures	Deployment of antenna, camera, RTG* booms on Voyager, Galileo	Reliable unfolding after launch of complex structures to within alignment servo capture, followed by locking of joints for rigidity	'97
Quiet Machinery	HST reaction wheels; 20 nm runout	Depends upon isolation and passive damping	'97

*RTG = Radioisotope Thermoelectric Generator
** D-strut = [Honeywell] damping strut

E. MATERIALS AND STRUCTURES FOR STIFF OPTICAL INSTRUMENTS

- Objective:

  Rigidly hold optical components

- Mission Enabled:

  POINTS

- Payoff / Performance:

  Stiff optical structures maintain the OPD in an interferometer in the presence of mechanical disturbance, reducing the need for vibration-reduction techniques.

- Required Technology:

Technology	Current State of the Art	Science Mission Requirement	Date Needed
Lightweight Optical Components	TBD	TBD	'97
Stiff Structures	Graphite-epoxy	Sufficient if augmented by structural quieting	'97

- Existing Efforts:

  Development of lightweight optics.

- Issues:

  Passive technology approach (e.g., increasing the ratio of structural mass to optical-component mass) vs. active technology approach (e.g., CSI).

F. THERMALLY STABLE OPTICAL ELEMENTS

- Objective:

Minimize the wave-front distortion and OPD shifts associated with changes in temperature and temperature gradient.

- Mission Enabled:

OSI, POINTS

- Payoff / Performance:

Reduced sensitivity to thermal environment.

- Existing Efforts:

TBD

- Required Technology:

Technology	Current State of the Art	Science Mission Requirement	Date Needed
Homogeneous and low CTE for mirror materials	ULE CTE of $2x10^{-9}/K$ for $(10\ cm)^3$ blocks claimed by Corning	TBD	'97
Low D* for transmissive optics	TBD	TBD	'97
High thermal conductivity for both transmissive and reflective optics	TBD	TBD	'97

*Note: D = dn/dt + (n-1)•(CTE), where n is the refractive index, t is the time, and CTE is the coefficient of thermal expansion.

- Issues:

Lightweight optics frequently made with large voids, resulting in lower effective thermal conductivity and larger distortions from thermal gradients

V. SUMMARY

The following section discusses projected OSI technology development funding requirements through Phase B, in FY93 dollars. A similar table for POINTS will be shown below. In section C, CSI funding will be discussed in detail, broken out separately for OSI and POINTS.

A. OSI FUNDING SCHEDULE AND MILESTONES

Technology / Year	FY93	FY94	FY95	FY96	FY97	FY98
Controls-Structures Interaction (CSI)	\$3.4M	\$4.5M	\$4.5M	\$4.0M	\$3.6M	----
Metrology	\$3.0M	\$3.0M	\$3.0M	\$3.0M	\$3.0M	\$3.0M
Active Delay Lines	\$2.0M	\$2.0M	\$2.0M	\$2.0M	\$2.0M	\$2.0M
Precision Deployable Structures	\$1.0M	\$1.0M	\$1.0M	\$1.0M	\$1.0M	\$1.0M
Total	**\$9.4M**	**\$10.5M**	**\$10.5M**	**\$10.0M**	**\$9.6M**	**\$6.0M**

OSI requires funding at about the \$6M level annually in addition to technology development funded under the CSI program:

<u>Metrology (\$3.0M/year)</u> (including precision optical fiducial development at around \$1M total)

Milestones:
- Demonstration of relative metrology ("laser gauges") to 5 pm accuracy in FY94, 0.5 pm in FY96
- Measurement of 3D motion of optical fiducials to 30 pm accuracy in FY94, 3 pm in FY96
- Measurement of 1D absolute distance to 10 μm
- Calibrate fiducial error to 20 pm in FY94, 3 pm in FY96

<u>Active Delay Lines (\$2.0M/year)</u> (in addition to \$1.5M to be covered by the CSI program)

Milestones:
- Designing an active delay line usable in zero-g
- Building an active delay line usable in zero-g
- Testing an active delay line usable in zero-g
- Control of optical paths to 10 nm

OSI TECHNOLOGY DEVELOPMENT
MAJOR MILESTONE SCHEDULE

Activities	FY 1993				FY 1994				FY 1995				FY 1996				FY 1997				FY 1998		
		1993				1994				1995				1996				1997				1998	
	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
METROLOGY																							
• Precision optical fiducial devel.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	▽				
• Demo. 1D rel. metrology to 0.5 pm								5 pm ▲								0.5 pm ▲							
• Meas. 3D rel. motion of optical fiducials to 3 pm								30 pm ▲								3 pm ▲							
• Meas. 1D abs. distance to 10 µm												▲											
• Calibrate fiducial error to 3 pm												20 pm ▲				3 pm ▲							
ACTIVE DELAY LINES (beyond CSI)																							
• Design zero-g active delay line	—	—	—	—	—	—	—	▽															
• Build zero-g active delay line									△	—	—	—	—	—	—	—	—	—	▽				
• Test zero-g active delay line																	△	—	▽				
• Control of optical paths to 10 nm								100 nm ▲											10 nm ▲				
PRECISION DEPLOYABLE STRUCTURES																							
• Design model deployable on ground	—	—	—	—	—	—	—	▽															
• Build model deployable on ground									△	—	—	▽											
• Test deployment of model on ground													△	—	—	▽							
• Flight-test deployable model																▲							

3/19/93

Precision Deployable Structures ($1.0M/year)

Milestones:

- Designing model deployable on the ground
- Building model deployable on the ground
- Testing deployment of model on the ground (leading to flight test)

Additional technology development milestones for OSI coincide with those of the CSI program (see section V.C, including CSI TECHNOLOGY FOR OSI __ FUNDING SUMMARY). *The funding profile for OSI outlined in this plan assumes continuation of the Micro-Precision CSI interferometer technology program funded at a funding level of $3.5-$4.5M/year through FY97.*

B. POINTS FUNDING SCHEDULE AND MILESTONES

The following section discusses projected POINTS technology development funding requirements through Phase B, in FY93 dollars. "CSI for POINTS" designates those CSI subtasks that can or will directly serve POINTS if it is selected as AIM; the CSI program, which is dedicated to technology development for future interferometry missions, may be directed to study certain generic technology issues not specific to AIM. On the other hand, the SAO team will carry out certain studies and develop certain analytical tools connected with structures and computer modeling when the POINTS team's approach differs significantly from that of CSI. For instance, they are developing advanced analytic models for optical systems, as opposed to numerical models such as IMOS/COMP (JPL). They will also study trade-offs of alternative Full-Aperture Metrology (FAM-A, FAM-B) techniques, in connection with their fiducial-block design and the placement of diffractive elements critical to the POINTS metrology scheme.

Technology/Year	FY93	FY94	FY95	FY96	FY97	FY98
Metrology	$1.80M	$2.93M	$4.65M	$4.73M	$2.65M	$1.80M
Prec. Opto-Mech. Sys.	$1.30M	$1.00M	$1.35M	$1.05M	$0.50M	$0.50M
Low CTE Materials	$1.00M	$1.15M	$0.80M	$0.10M		
CCDs	$0.50M	$0.85M	$0.95M	$0.95M	$0.95M	
Adv. Opt. Modeling	$0.10M	$0.35M	$0.25M	$0.25M		
CSI for POINTS	$2.65M	$3.50M	$3.60M	$3.30M	$2.55M	
Total	**$7.35M**	**$9.78M**	**$11.60M**	**$10.38M**	**$6.65M**	**$2.30M**

POINTS Technology Development Milestones

FY93:

- Metrology:
  - • Begin design, fabrication and testing components for space

- Precision Optomechanical Systems:
  - • Begin optical bench design
  - • Design instrument box
  - • Begin design of articulation mechanism
  - • Begin design of low-cost, low-precision pointing system
  - • Carry out Reaction Wheel Assembly (RWA) reduction study
  - • Begin RWA life study

- Low CTE Materials:
  - • Continue testing homogeneity of ULE
  - • Continue studies of wavefront in transmission for ULE
  - • Continue development of lower CTE ULE

- Advanced Optical Modeling:
  - • Begin developing analytic (vs. numerical) computer models
  - • Begin developing advanced numerical modeling tools, e.g., COMP

- Begin developing High QE CCDs for spectrometers

FY94:

- Metrology:
  - • Extend capability to 0.5 pm
  - • Begin fiducial block fabrication

- Precision Optomechanical Systems:
  - • Begin evaluating optical bench
  - • Complete design of articulation mechanism
  - • Complete design of low-cost, low-precision pointing system
  - • Carry out Reaction Wheel Assembly (RWA) reduction study
  - • Complete RWA life study

- Low CTE Materials:
  - • Complete testing homogeneity of ULE

- Advanced Optical Modeling:
  - • Carry out study of FAM-A vs. FAM-B trade-offs

FY95:

- Metrology:
  - • Make endpoint and dimple-plate, begin testing
  - • Begin beam injection and beam steering studies
  - • Fabricate Holographic Optical Element (HOE) and begin testing

- Precision Optomechanical Systems:
  - • Complete optical bench design
  - • Begin building and testing articulation mechanism

- Low CTE Materials:
  - • Complete development of lower CTE ULE

FY96:

Metrology:

- • Complete testing of endpoint and dimple plate
- • Carry out extended-range distance measurement
- • Complete fiducial block fabrication
- • Complete beam injection studies

- Precision Optomechanical Systems:
  - • Complete optical bench evaluation
- Low CTE Materials:
  - • Continue testing homogeneity of ULE
  - • Continue studies of wavefront in transmission for ULE
  - • Continue development of lower CTE ULE

- Advanced Optical Modeling:
  - • Begin developing analytic computer models
  - • Begin developing advanced numerical modeling tools, e.g., COMP

- Begin developing High QE CCDs for spectrometers

FY97:

- Carry out rapidly changing distance measurement
- Complete beam steering studies
- Complete HOE testing, carry out precision HOE test

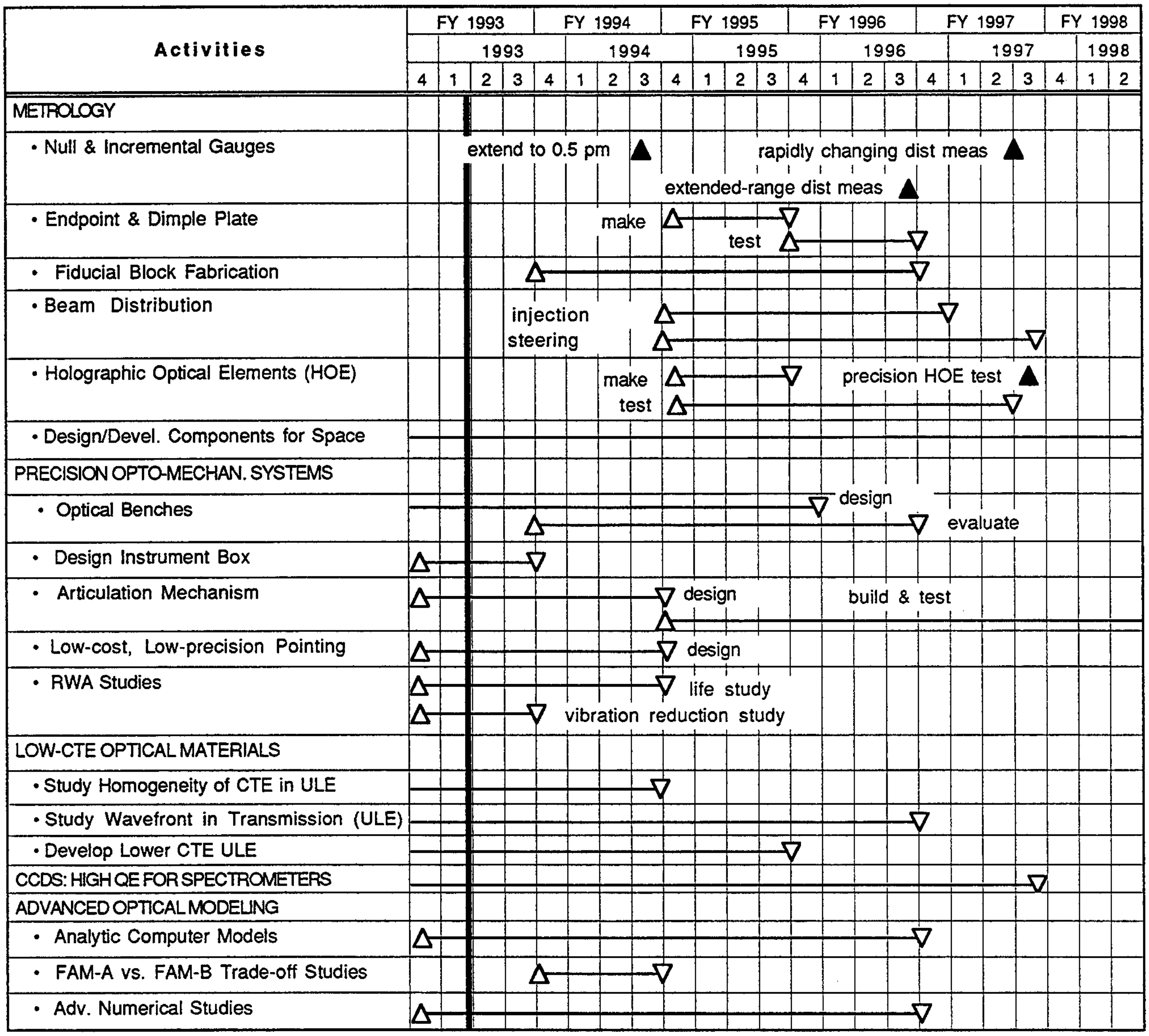
FY98:

- Complete design, fabrication and testing of components for space

POINTS TECHNOLOGY PLAN (EXPANDED)
(FY93$K)

TASK (subtotals) / FISCAL YEAR	FY93	FY94	FY95	FY96	FY97	FY98	TOTAL
Metrology	**1800**	**2925**	**4650**	**4725**	**2650**	**1800**	**18550**
• Extend to 0.5 pm		125					125
• Make endpoint & dimple plate			225				225
• Test endpoint & dimple plate			225	225			450
• Extended-range distance meas.				450			450
• Rapidly changing distance meas.					350		350
• Components for space	1800	1800	1800	1800	1800	1800	10800
• Fiducial block fabrication		1000	1000	1000			3000
• Beam injection			500	500			1000
• Beam steering			400	450	200		1050
• Make HOE			100				100
• Test HOE			400	300	175		875
• Precision HOE test					125		125
Precision Opto-Mech. Systems	**1300**	**1000**	**1350**	**1050**	**500**	**500**	**5700**
• Design optical benches	150	150	150				450
• Evaluate bench		250	1000	500			1750
• Design instrument box	150						150
• Design, build & test articulation mechanism	150	150	200	550	500	500	2050
• Design low-cost, low-precision pointing	150	150					300
• Reaction wheel (RWA) life study	300	300					600
• RWA vibration reduction study	400						400
Low CTE Materials	**1000**	**1150**	**800**	**100**	**0**	**0**	**3050**
• Test homogeneity of ULE	300	350					650
• Wavefront in transmission for ULE	100	100	100	100			400
• Develop lower CTE ULE	600	700	700				2000
High QE CCDs for Spectrometers	**500**	**850**	**950**	**950**	**950**	**0**	**4200**
Advanced Optical Modeling	**100**	**350**	**250**	**250**	**0**	**0**	**950**
• Advanced analytic optical computer models	100	250	250	250			850
• FAM-A vs. FAM-B tradeoff analysis		100					100
CSI for POINTS	**2650**	**3500**	**3600**	**3300**	**2550**	**0**	**15600**
• Design, build & study POINTS-like testbed	700	1150	1200	1100	1200		5350
• Develop IMOS/COMP	400	400	300	300	300		1700
• Apply IMOS/COMP to POINTS	200	200	300	400	400		1500
• Advanced numerical modeling, e.g., COMP	150	500	500	500			1650
• Des. & eval. struc., dev. & apply dampers	300	300	300	200	150		1250
• Develop RWA & instrument isolators	400	600	600	500	350		2450
• Optical Compensation -- Fine Pointing	500	350	400	300	150		1700
TOTAL	**7350**	**9775**	**11600**	**10375**	**6650**	**2300**	**48050**

POINTS TECHNOLOGY DEVELOPMENT
MAJOR MILESTONE SCHEDULE
(in addition to CSI)



3/19/93

C. CSI FUNDING SCHEDULE AND MILESTONES

In the following tables and milestone chart show the required funding levels for continuation of the Micro-Precision CSI Program at JPL for the development and testing of interferometer technology in support of AIM. Separate funding profiles have been provided for both candidate missions, OSI and POINTS. Since the "down-select" will not take place this year, FY93 funding levels are the same for both candidates.

FY93:

- Deliver micro-precision interferometer (MPI) testbed, Phase 1 configuration, ready for initial testing (will probably carry over into FY94 due to current funding level and deferral of the AIM down-selection)
    - active delay line for single baseline
    - pointing & tracking optics for single baseline
    - internal metrology for delay line
    - star simulator metrology for single baseline
- Complete fab. & test of single-axis prototype vibration-isolation system
- Complete design of 1st gen. active & passive members for MPI testbed
- Document results of filled aperture focus mission study; discont. activity

FY94:

- Initial end-to-end operation of MPI testbed
- Deliver 5 passive & 5 active members to MPI testbed
- Complete design of 6-axis vibration isolation system

FY95:

- Complete testing on MPI Phase 1 configuration
- Complete designs of
    - Flight traceable active delay lines
    - POINTS fine pointing system
    - Active & passive members
- Deliver version 1.0 integrated modeling & design s/w

FY96:

- Deliver delay lines, pointing systems, members to MPI
- Complete MPI two-baseline (Phase 2) configuration build

FY97:

- Demonstrate CSI technology on Phase 2 MPI testbed at 10-nm rms level

CSI TECHNOLOGY FUNDING SUMMARY (FY93$K)

(AIM/OSI version)

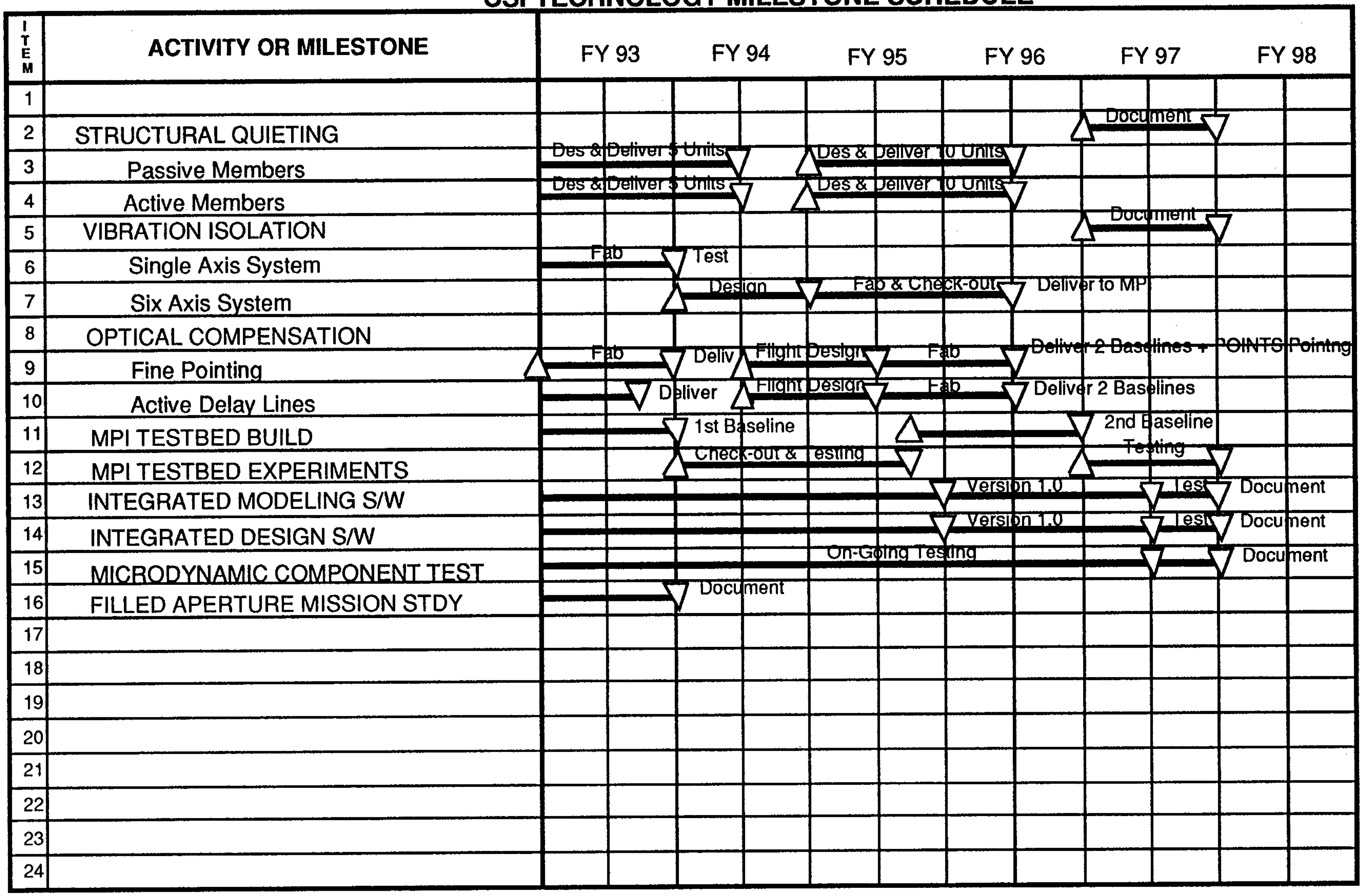
TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97	TOTALS
Structural Quieting	300	400	400	300	250	1650
• Passive Members						
• Active Members						
Vibration Isolation	400	600	600	500	350	2450
• Single Axis System						
• Six Axis System						
Optical Compensation	500	650	800	600	300	2850
• Fine Pointing						
MPI Testbed Build*	900	700	250	1600		3450
MPI Testbed Experiments		1000	1250		1700	3950
Integrated Modeling Software	400	350	350	300	300	1700
Integrated Design Software, Adv. Num. Mod.	350	350	400	300	300	1700
Microdynamic Component Tests	150	150	100	100	100	600
Filled Aperture Mission Studies	100					100
Flight Interferometer Design Studies	300	300	300	300	300	1500
TOTALS	**3400**	**4500**	**4450**	**4000**	**3600**	**19950**

(AIM/POINTS version)

TECHNOLOGY	FY 93	FY 94	FY 95	FY 96	FY 97	TOTALS
Structural Quieting	300	300	300	200	150	1250
• Passive Members						
• Active Members						
Vibration Isolation	400	600	600	500	350	2450
• Single Axis System						
• Six Axis System						
Optical Compensation	500	350	400	300	150	1700
• Fine Pointing						
MPI Testbed Build*	900	250	200	1100		2450
MPI Testbed Experiments		900	1000		1200	3100
Integrated Modeling Software	400	400	300	300	300	1700
Integrated Design Software, Adv. Num. Mod.	350	700	800	900	400	3150
Microdynamic Component Tests	150	150	100	100	100	600
Filled Aperture Mission Studies	100					100
Flight Interferometer Design Studies	300	300	300	300	300	1500
TOTALS	**3400**	**3950**	**4000**	**3700**	**2950**	**18000**

**MPI Testbed Build includes $200K in overlapping funding to cover work until AIM down-select*

CSI TECHNOLOGY MILESTONE SCHEDULE



D. TECHNOLOGY TRANSFER

Commercial Potential of OSI Technology:

The following is a partial listing of suggested commercial applications of key technologies being developed for OSI:

Picometer metrology

- Very high precision X-Y stages for integrated circuit mask locating and aligning. For example, small masks can be repeated with great accuracy to make larger masks.
- Very high precision laser and electron-beam machining to produce highly repeatable, very uniform structures.
- Surface figure and surface roughness measuring apparatus.
- Suspension control of gravitational wave experiments on Earth (e.g., LAGOS, LINE).
- Possible replacement for Optical Time Domain Reflectometry (OTDR) for high-precision distance for measurements ranging from surveying to optical-fiber defects. (See discussion of absolute metrology below.)

Stable lasers

- Heterodyne laser communications systems, esp. for space applications.
- Instruments for precision *in situ* spectroscopy .
- Laser "radar"
- Instruments for "light science" (laser analog of radio science: using on-board lasers transmitting signals to Earth to probe planetary atmospheres, the interplanetary medium, etc.).

Optical detectors

- Ground-based astronomy.
- Low-light-level imaging systems.
- Space laser communications systems.
- Optical/near IR astrophysics, planetary, Earth-observing missions.

Absolute metrology

Absolute metrology is being developed for OSI to an accuracy of ~10 μm, which represents an improvement of two orders of magnitude over methods used today. Absolute distance is currently determined using pulsed time-of-flight measurements with accuracies of ~1mm. Numerous applications, from surveying using shorter baselines for triangulation, to OTDR of integrated optics defects, can benefit from improved absolute metrology.

Many sensors have been developed that use interferometric measurement of optical fiber length, including acoustic, temperature, electric field, and magnetic field sensors. Absolute metrology of fiber length decouples length measurement from fringe counting of a incremental (relative metrology) laser system. Relative metrology requires continuous fringe counting; when this process is interrupted -- e.g., when acoustic sensors are used to monitor fibers associated with explosives -- the metrology system fails. An absolute metrology system can measure fiber length before detonation, be turned off until transient effects have decayed, and then turned on again to measure fiber length after the event.

Commercial Potential of Micro-Precision CSI Technology:

The Micro-Precision CSI program has already made an important contribution to NASA with respect to the transfer of technology to space missions. To date, the single most significant beneficiary of this technology transfer has been the Hubble Space Telescope (HST) Repair Mission. Solid state electrostrictive actuator technology, whose application to precision control was brought to maturity in the CSI active member, has been used in the Articulating Fold Mirror (AFM) of the replacement Wide Field Planetary Camera (WF/PC-2), scheduled for installation in HST late in 1993. Another instance of technology transfer to the HST Repair Mission is the use of the Controlled Optics Modeling Package (COMP), a Micro-CSI developed software tool, to perform "prescription retrieval" on HST's aberrated optical system, assuring that the corrective optics to be installed in the repair operation have been designed with the proper optical prescription. In addition to AIM, any future NASA mission with the need for a high level of precision in alignment and dynamic stabilization is a good candidate for the transfer of micro-precision CSI technology. Such missions include a broad class of future optical systems as well as micro-gravity science payloads requiring vibration isolation.

CSI technology may be applied to a wide variety of commercial products and processes:

- Automotive applications: active members as smart shock absorbers, piezoelectric appliques for quieting plate vibrations in roof panels and for serving the purpose of an "electronic" muffler by acoustically cancelling engine noise. Germany is already working on each of these areas.

- Piezoelectric polymers have already been applied to quiet vibrations in the tiny beams supporting the magnetic read heads in computer hard disks.

- Potential advantages, e.g., in low-voltage source applications, may result from the use of electrostrictors or magnetistrictors that have been studied in depth by Micro-Precision CSI.

- Japan is looking at the use of large motion adaptive truss structures, which, because of the high stiffness-to-mass ratio inherent in a truss, could be used for high-speed robotic assembly. Marriage of this technology to micro-precision structural quieting could offer a cost-effective alternative to the multi-tiered dextrous robot.

- Vibration isolation technology under development by the Micro-Precision CSI program could find broad application in the field of machinery quieting.

- CSI work in high-fidelity finite-element modeling and model-correlation techniques could find application in industries as diverse as the automotive and machine tool industries, which depend heavily on finite-element codes for loads and dynamic analysis.

These candidates for technology transfer to the commercial sector fall under several headings of "emerging technologies" as defined by the Commerce Department: advanced materials, artificial intelligence, high-performance computing, and sensor technology. The Micro-Precision CSI program thus has the potential to serve not only as a catalyst for cooperation between NASA and US industry, but for joint international ventures as well.

E. PROJECT MANAGEMENT

The management responsibility for the technology development tasks described in this plan will rest with a Study/Project Technologist, who will also be the Deputy Study/Project Manager and report to the Study/Project Manager. The Study/Project Technologist resides at the NASA center that has overall responsibility for the project.

As part of his or her responsibilities, the Study/Project Technologist will ensure that the technology development is technically sound, up-to-date, and within acceptable risk and cost, and that it meets the project's system engineering and integration requirements.

The goal of the technology development tasks is to determine and demonstrate the best possible technical solutions to the project's engineering and technical challenges. To achieve this goal, participation will be solicited from interested and capable parties at universities, in industry, and at Federal laboratories, including NASA centers. Consideration will be given to proposals ranging from traditional approaches, requiring only minor extensions beyond current technical capabilities, to radical approaches for solving the project's engineering and technical challenges.

It is anticipated that initially, for each task, parallel paths will be pursued in solving the challenges; and that, in each case, from those paths the best solution will be down-selected for final development and demonstration. Clear descriptions of these parallel paths, including milestones and decision points, as well as adherence to the schedule, will be required. Teaming arrangements, possibly involving universities, industry, NASA centers, and other Federal laboratories, will be strongly encouraged.

F. INTERFEROMETER TECHNOLOGY OVERALL DEVELOPMENT PRIORITIES

HIGHEST:

- Metrology (POINTS and OSI)
- Fine Pointing with Isolation (POINTS)
- Active Delay Lines (OSI)
- Quiet Structures and Subsystems (POINTS and OSI), Precision Deployment (OSI)

HIGHER:

- Materials and Structures for Stiff, Low-Expansion Optical Instruments including Bent Optical Paths (POINTS)
- Thermally Stable Optical Elements (POINTS and OSI)

HIGH:

- None

IV.A Advanced Concepts Studies

In order to plan for the longer-term future, the Astrophysics-Technology Team (ATT), established jointly by the Astrophysics Division and OACT, recognizes the need to conduct advanced concepts studies. These studies will build on the knowledge that was obtained during the earlier phases of the AstroTech 21 program. The topics that were studied in the earlier phases were the following:

- Optical Interferometry in Space
- Submillimeter Interferometry in Space
- Laser Gravitational Wave Observatory in Space
- Advanced Very Long Baseline Interferometry in Space
- Large Filled-Aperture Telescopes in Space

Additional studies are needed to address such issues and topics as:

- The scientific roles of interferometers vs. large filled aperture telescopes in space
- Lunar basing vs. high earth orbit basing for optical interferometers and large aperture telescopes
- Future missions of high energy astrophysics
- Low frequency radio astronomy

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

NASA

Reply to Attn of: PS02 November 16, 1992

TO: Code SZH/Mike Kaplan

FROM: MSFC/PS02/Max Nein

SUBJECT: Applied Technology Requirements for LUTE

As requested during our meeting in Headquarters on November 12,1992, we are providing you a listing of applied technology items, which need to be considered for funding in FY 1993.

We have identified these key areas of applied technology requirements based on system and subsystem assessments for LUTE and on our understanding of the current state of technology in these areas. The outlined subject areas are very specific and urgent for the LUTE project and we are ready to conduct these task immediately, if funding becomes available.

We can further enhance these brief summary statements and will present more details to you and/or Code R, if necessary. Please contact Robert McBrayer or myself for further clarification. I can be reached at 205-544-0619 and Mr. McBrayer at 205-544-1926.

M. E. Nein
LUTE Deputy Study Manager

cc:
PA01/C. Darwin
PF21/R. McBrayer
PS01/H. Gierow

The following tasks describe LUTE specific technology areas which need to be initiated in FY 1993 for development. The total funding requirement is
$ 1575 K, as a first estimate.

AVIONICS TEMPERATURE CONTROL

The extreme delta temperature of a lunar day/night cycle coupled with non-operational conditions during the lunar night (as dictated with a solar array power system for LUTE) requires avionics components and system to operate well beyond the qualification limits. This creates unknown engineering risk in the development of LUTE avionics systems.

To understand and quantify this engineering risk, an applied technology and development program is needed to explore techniques for design, packaging and thermal control of electrical and electronic avionics systems.

The technology effort proposed is the investigation of a common and integrated packaging concept that will integrate all thermal sensitive circuits and components with a passive thermal control technique. The ultimate goal is to manage and store the waste operational heat of the avionics system during lunar day operation and utilize this stored heat to maintain an acceptable storage temperature during lunar night when the avionics is non-operational.

($150K)

POINTING ALIGNMENT SYSTEM

Telescope Mount

- Applied Technology development for a lightweight, stiff, simple telescope mount that can provide:
  - +180° azimuth capability, at +1° accuracy
  - ~45° elevation capability, at +5 arcmin accuracy
  - +180° roll capability, at +15 arcsec accuracy

($100K)

- Design and development of a telescope mount that can meet precision alignment requirements without the use of a control system to accommodate thermal deformations over a wide range of temperatures

($100K)

Sensors

- Technology development of alignment sensors that provide accurate measurement over a wide range of temperatures, and are insensitive to lunar dust

($50K)

Adaptive Optics

- Technology development of lightweight secondary mirror actuation system that does not increase the obscuration ratio of the telescope

($25K)

- Technology development of an actuated deformable primary mirror that will maintain an optical surface within100 Å in a lunar thermal environment

($150K)

- Technology development of an active metering structure that will accommodate large thermal gradients (typically 70 K)

($75K)

- Development of an integrated multibody dynamics program that has the capability to dynamically model the thermal loads on a interconnected set of structures, using environment-dependent material properties (ie., temperature dependent properties), and interface with control-system development software, and optical analysis software

($100K)

DETECTOR THERMAL CONTROL

Understanding the performance of the CCD detector in the harsh lunar environment is very important in determining design features of the optical system and possibly the feasibility of the LUTE all together. For these reasons a detailed thermal analysis of the detector and its components and also some testing to the temperature extremes of the lunar environment of a typical 5-7 mm pixel size CCD are needed. This technology task will define the best thermal control system for the detector, and includes development of thermal models, analysis and evaluation of a CCD design, and testing of a CCD at simulated LUTE focal plane conditions.

($150)

OPTICAL SYSTEM

Optical Coatings:

Investigate the durability and optical performance of high reflectance coatings for the 1000-3000 Å band, both as freshly applied ("new") and after exposure to a simulated lunar environment (temperature, vacuum, dust, potential contaminates, etc.) The MSFC Optics and RF Division has the capability to produce thin film coatings. Environmental testing could be done by the Materials and Processes Lab, or by an outside testing group (university or industry).

($100K)

Large Area Detectors:

Explore capability of industry to produce large area CCD detectors either fabricated directly on a spherical substrate or sufficiently thin that they could be "stretched" to conform to a spherical surface, to allow matching the detector to any image field curvature in the LUTE (and other) telescope(s).

($25K) survey

Buy unmounted CCD's, investigate mounting techniques and effect on optical and electrical characteristics. Work to be done by the Optics and RF Division, with potential collaboration from the Electronics Components and Packaging Division.

($50K)

Wavefront Sensor:

Survey current state-of-the-art in wavefront sensors and expected advances in next 3-5 years. Study operating requirements and compatibility with the LUTE/lunar environment (cold soak, heat, radiation, etc.) Develop matrix showing data rates, update rate, etc.

($50K)

Telescope Breadboard:

Develop a scaled breadboard to evaluate an athermalized design incorporating active control where required.

($300K)

MIRROR MATERIALS

The optical system of LUTE, with its passive thermal control, has to withstand large temperature swings in the range of 70° - 375°K. The optical performance of various mirror materials and their degradation during thermal cycling is of primary importance to the feasibility of LUTE. Historically space optical systems have been operated at the manufacturing temperature or at a constant temperature for which the optical prescription has been biased during manufacture. In the case of LUTE this is not possible because of the continuously changing temperatures during the lunar cycle (primarily in the day time portion). Therefore a literature study on property variations, and some selective testing is required to evaluate a suitable mirror material. Candidate materials are beryllium, silicon carbide, ULE.

($ 150K)

Relativity/Gravitational Physics – Program Goals

- Detect low frequency (LF) gravitational waves
- Detect frame-dragging by a rotating earth
- Improve determination of PPN parameters via solar system dynamics
- Improve limits on $\dot{G}$ via solar system dynamics
- Improve limits on possible equivalence principle violations
- Detect second-order gravitational redshift

Ηativity/Gravitational Physics – Missions

- Laserⁱravitational Wave Antenna in Space (LINE, LAGOS, etc.)
- Gravi Probe B
- LAG)S III
- Rangg to planetary missions (Mercury Orbiter, Icarus Lander, etc.
- Satelb Test of the Equivalence Principle (STEP)
- Earthrbit or solar probe redshift experiments (trapped ion or H-ıser clocks)

Relativity/Gravitational Physics – Technology Development

Major need is technology for gravitational wave detection

- Spaceborne Frequency Standards
- Laser Tracking Systems
- Laser optics, pointing, and control
- Drag-free systems
- Spacecraft thermal stability
- Mission studies and science development

Spaceborne Frequency Standards

- Relativity ATD support has allowed cryogenic H-Maser to be tested
- Future development of space cryogenic H-masers needed
- Trapped mercury ion standards have demonstrated long-term stability with low weight and power
- Relativity ATD support in FY'91 allowed ytterbium ion trap to be constructed and tested
- Future tasks in ytterbium trap development
  - develop flight microwave instrument
  - laboratory test of optical standard
  - couple optical standard to laser system

Laser Tracking Systems

- Demonstration of phase-locking lasers (completed)
- Demonstration of phase-lock to weak signal (requires 1 year)
- Design and construction of prototype laser transponder
- Stabilization of laser with Ytterbium trapped-ion standard

Laser optics, pointing, and control

- Design for LAGOS pointing system (currently funded)
- LAGOS optical system design
- Laboratory tests of optical system
- Laboratory tests of pointing system

Drag-free systems

Accelerometer technology

- GRADIO accelerometer developed for ARISTOTELES with sensitivity 1×10^{-12} m s^{-2} Hz$^{-1/2}$
- Earth-orbiting laser interferometer requires 3×10^{-13} m s^{-2} Hz$^{-1/2}$
- GRADIO II design needed with more massive proof mass, improved symmetry of internal core, reduced proof-mass gaps, better thermal environment

Reaction Control Thrusters

- Field Emission Electric Propulsion (FEEP) units have been developed at ESTEC (tested, never used)
- Units need to be acquired for tests of
  - thrust stability
  - cycling lifetime
  - cesium contamination of optics

MAR 4 '92 15:33 FROM JPL OSSI PAGE.009

Spacecraft thermal stability

- Optical path stability and accelerometer cavity stability require 10^{-4}K Hz$^{-1/2}$ in the band
- IMOS program (Integrated Modeling of Optical Systems) will provide combined optical/thermal/structural modeling capability
- Laser interferometer missions need to be included in IMOS mission definition set

Mission studies and science

- Scientific rationale and operations scenario needs continuing development
- Orbit characteristics and instrument requirements need parallel development
- Spacecraft weight, launch capabilities, and trajectory design need parallel development

ATD Budget (K$)

FY's 1991-2000

Technology	FY 91	92	93	94	95	96	97	98	99	00
Space Frequency Standards	80	20	60	70	100	150	200	250	250	250
Laser Tracking Systems	–	–	40	50	80	100	150	200	200	200
Laser Optics & Pointing	130	100	100	100	120	150	200	200	200	200
Drag-Free Systems	–	–	–	40	100	150	100	150	150	150
Spacecraft Thermal Stability	–	–	20	50	50	50	100	100	100	100
Mission Studies & Science	40	20	30	40	50	50	100	100	100	100
TOTALS	250	140	250	350	500	650	850	1000	1000	1000
Code SZ	200	120	200	250	250	250	250	250	250	200
Code RS	50	20	50	100	250	400	600	750	750	750

Relativity/Gravitational Physics - Program Management Plan

- Peer-reviewed technology development program
- Project management at Marshal SFC - R. Decher, Project Manager
  manages program, issues NRA, oversees grants
- Project scientific direction at JPL - R. Hellings, Project Scientist
  determines technology goals, organizes peer-review committee

03/19/93

Future Space VLBI
Introduction

- Purpose
  - Define a strawman mission for the next-generation Space VLBI platform, and identify the developments needed to make that mission a reality
- Personnel
  - R. Freeland, G. Levy, D. Meier, D. Murphy, R. Preston, J. Smith, J. Ulvestad
  - Advice from Project Science Group for U.S. Space VLBI Project
- Possible options
  - Option 1: Develop mature U.S.-only concept, with corresponding technology development to allow a new start by 2000
  - Option 2: Design concept that can be shared among various nations so that U.S. share can fit into Mid-Ex financial constraints, allowing new start before 2000
    - — Example: U.S. hybrid-inflatable antenna, European receivers, Japanese spacecraft systems, Russian launch vehicle

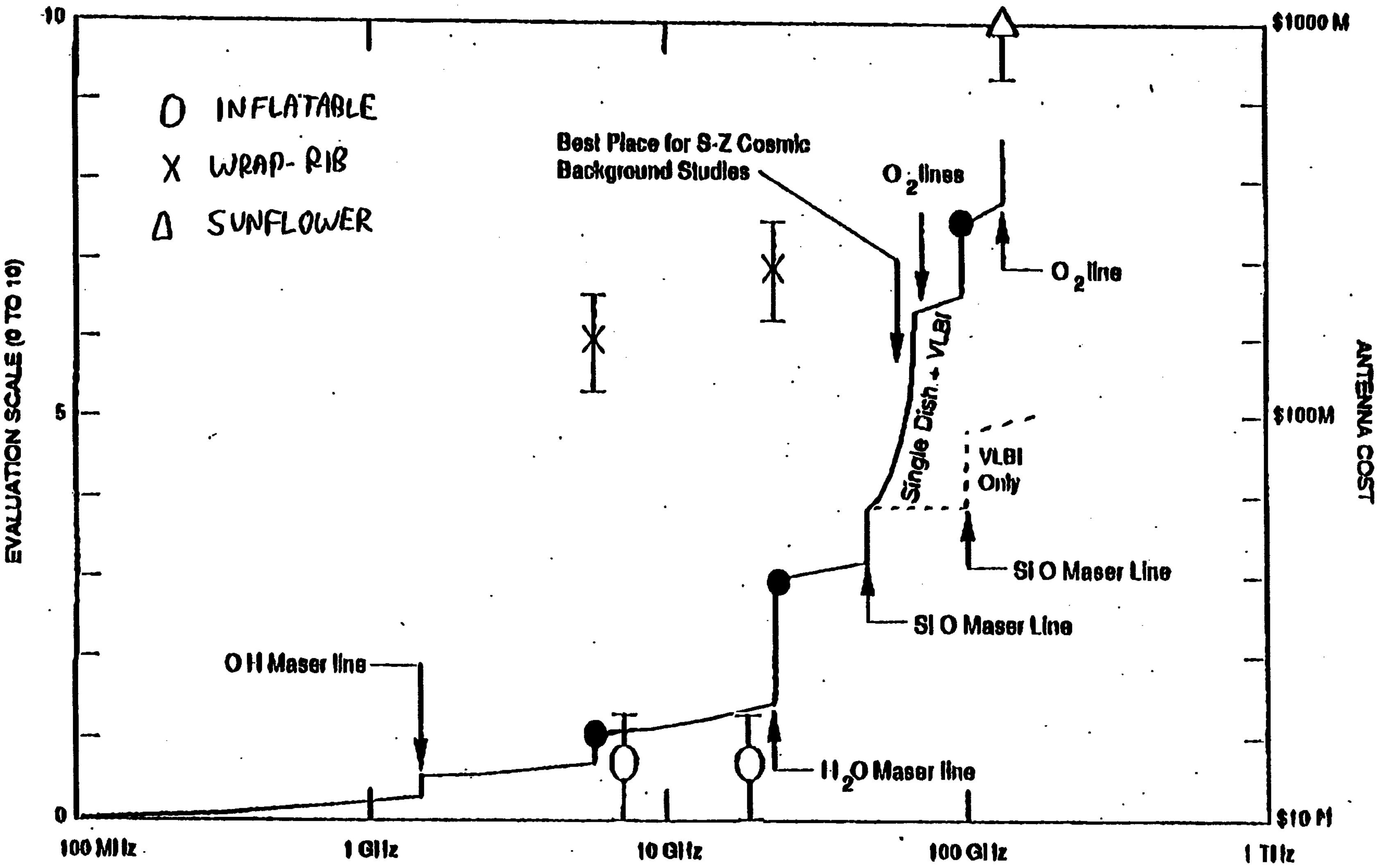
Future Space VLBI
SVLBI concepts and evolution

- 1) Technology demonstration
  - TDRSS: series of technology demonstration and feasibility experiments led by JPL in 1986–1988
    - — 4.9-m antenna with very limited capability at 2.3 and 15 GHz
- 2) Experiments (strong NASA and international participation)
  - Radioastron: Russian mission scheduled for launch in 1996/1997
    - — 10-m antenna operating at 0.3, 1.6, 5, 22 GHz
  - VSOP: Japanese mission scheduled for launch in 1995
    - — 8-m antenna operating at 1.6, 5, 22 GHz
- 3) Observatory (2000–2010 time frame)
  - **What comes next?** Astrotech-21 workshop in February 1991
    - — $75K of study money at JPL in FY92 ($50K from Code SZ, $25K from Code R)

Future Space VLBI
Main science goals

- Active galactic nuclei (AGN)
  - Continuum imaging of compact AGN at high dynamic range and sensitivity
  - < 50-μas imaging of AGN at 43 GHz
    - — Early evolution of outbursts in AGN
    - — High-frequency imaging of cores of self-absorbed radio sources
  - Statistical study of brightness temperatures as function of other source properties
- High-resolution mapping of sources with unbeamed cores (Seyfert and "normal" galaxies)
- Mapping and proper motions of galactic and extragalactic H_2O masers
  - Determination of Hubble's constant
- Imaging of radio stars
- Single-dish observations of O_2 and Sunyaev-Zel'dovich effect

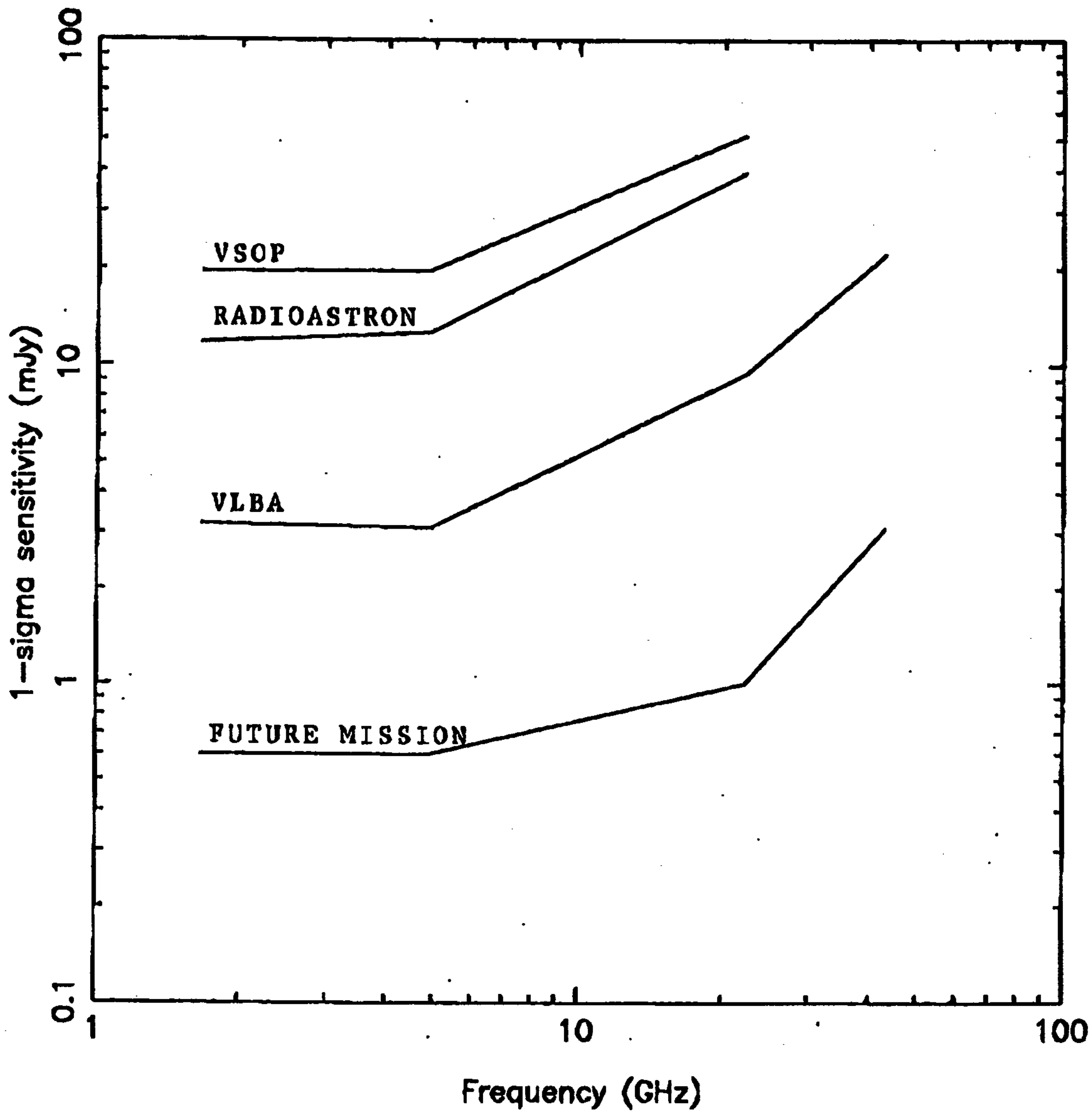
Future Space VLBI
Antenna costs and science vs. highest frequency



Future Space VLBI
Strawman mission selection

- One or two space antennas working at VLBA frequencies, with sensitivities better than a VLBA telescope
  - Frequency coverage to 43 GHz for VLBI, some area good to 60–70 GHz for single-dish studies of atomic oxygen, Sunyaev-Zel'dovich effect
  - Sensitivity to be achieved by combination of large antenna size, low system temperatures, and wide observing bandwidth
    - — Require interferometer sensitivity 1.5–2 orders of magnitude better than for baselines to VSOP and Radioastron
      - — Data rate = 1 Gigabit/s
      - — Antenna diameter = 25 m with 60% efficiency (50% at 43 GHz)
      - — System temperature = 10 K (20 K at 43 GHz)
      - — Coherent integration = 5 minutes (2 minutes at 43 GHz)
- Moderate cost ($\leq$\$400 million) international mission
- Five-year lifetime
- Orbit(s) to be selected depending on results of VSOP and Radioastron
  - Vary orbit(s) over mission lifetime

Future Space VLBI
Sensitivity vs. frequency on baseline to VLBA antenna

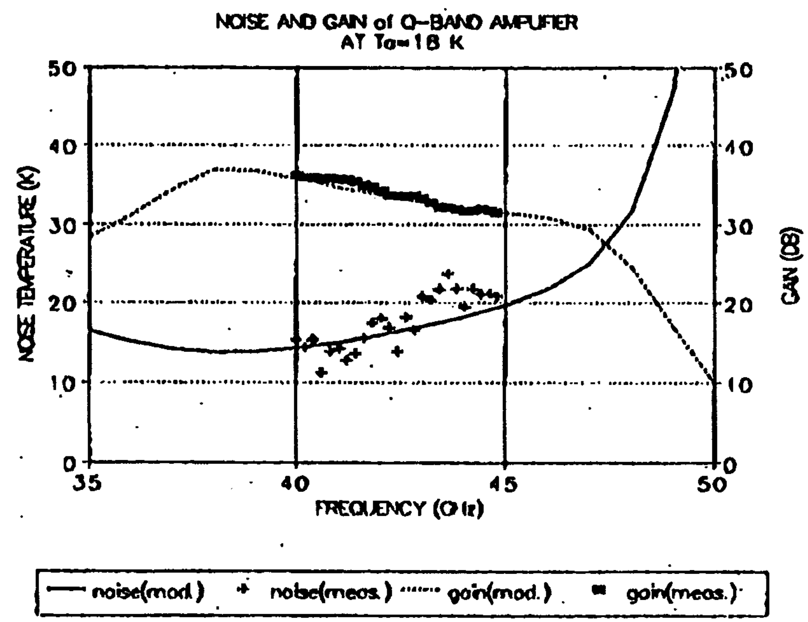


Future Space VLBI
Antenna technology

- 25-m antenna must be deployed reliably and cost no more than about $100 million, yet have a surface good to 43 GHz with an inner surface that works with some efficiency to ~70 GHz
- Antenna concepts
  - INSTEP flight experiment to test inflatable 14-m surface in 1995
    - Entire experiment cost is $5 million
    - Experiment goal is surface r.m.s. better than 1 mm
  - Hybrid (inflatable plus more rigid structure) to give required surface accuracy
    - If INSTEP experiment is successful, it may be possible to build a space 25-m antenna good to 22 GHz for well under $25 million
  - Smaller (15-m) wrap-rib antenna
    - Cost-effective compensation for smaller antenna size by doubling bandwidth relative to strawman
    - 25-m wrap-rib antenna good to 43 GHz probably would cost several hundred million dollars

Future Space VLBI
Recent progress on low-noise amplifiers

- Desire system temperatures of 10 K or less (20 K at 43 GHz)
  - Require ambient temperature of ~ 12 K, space qualification
  - Require low-mass, low-power, closed-cycle refrigerators with 5-yr lifetimes
  - Quantum limit for amplifiers is 0.1 K/GHz
- NRAO and TRW recently demonstrated a 40–45 GHz amplifier with noise temperature of 15 K at ambient temperature of 18 K (Pospieszalski, *et al.* 1993)



Modeled and measured performance of the Q-band amplifier at room and cryogenic temperatures.

Future Space VLBI
Other issues

- Data rate
  - Maximum (unsustainable) VLBA data rate is 512 Megabit/s
  - Mk IV system under development at Haystack will provide 1 Gigabit/s by 1995–1996, with possible expansion to 2 Gigabit/s
- Downlink bandwidth
  - World Administrative Radio Conference (1992) allocated 0.5 GHz of downlink bandwidth for space research at 40.0–40.5 GHz (uplink in 37–38 GHz band). Space research is a primary, but not exclusive, user of this band. Secondary allocation requested at 74–84 GHz.
  - Potential of optical communications?
  - Recording on spacecraft for "burst-mode" VLBI at 43 GHz?
- Coherence of phase link or onboard clock
- Availability of adequate tracking stations
- Capability for orbit evolution during mission

Future Space VLBI
Summary

- Strawman science mission is significant advance over current experimental missions and over ground-only VLBI with VLBA
  - Key advance is in sensitivity
    - — Strongly recommend INSTEP experiment to demonstrate feasibility of low-cost antenna with good surface
      - — Conceptual design of hybrid-inflatable antennas is needed as follow-on to INSTEP experiment
    - — Beyond 25–30 m aperture diameter, lowering system temperature and increasing bandwidth may be much more cost-effective sensitivity improvements than trying to construct a larger antenna
- Efforts to go to higher frequencies (90 GHz and above) will be very costly in antenna technology
- Most immediate need for work is in antenna technology and development of long-lasting cryogenic receiver and cooling systems for space

J. S. Ulvestad
ISRMOWG

A TWO-ELEMENT LOW FREQUENCY INTERFEROMETER (TELFI)

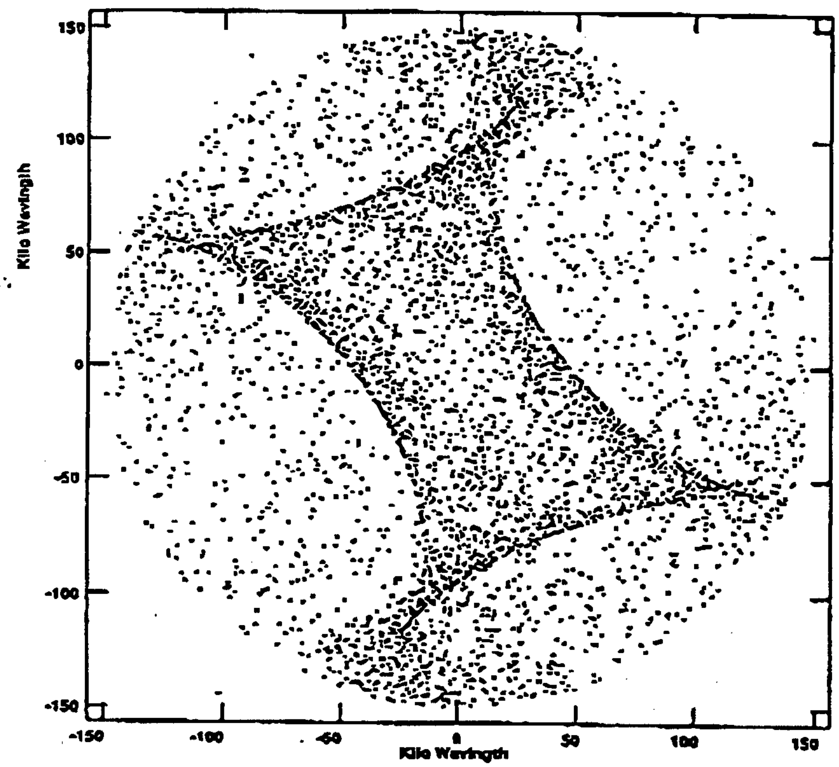
JACK O. BURNS
Department of Astronomy
New Mexico State University

Advantages of a Two-Element Orbiting Interferometer

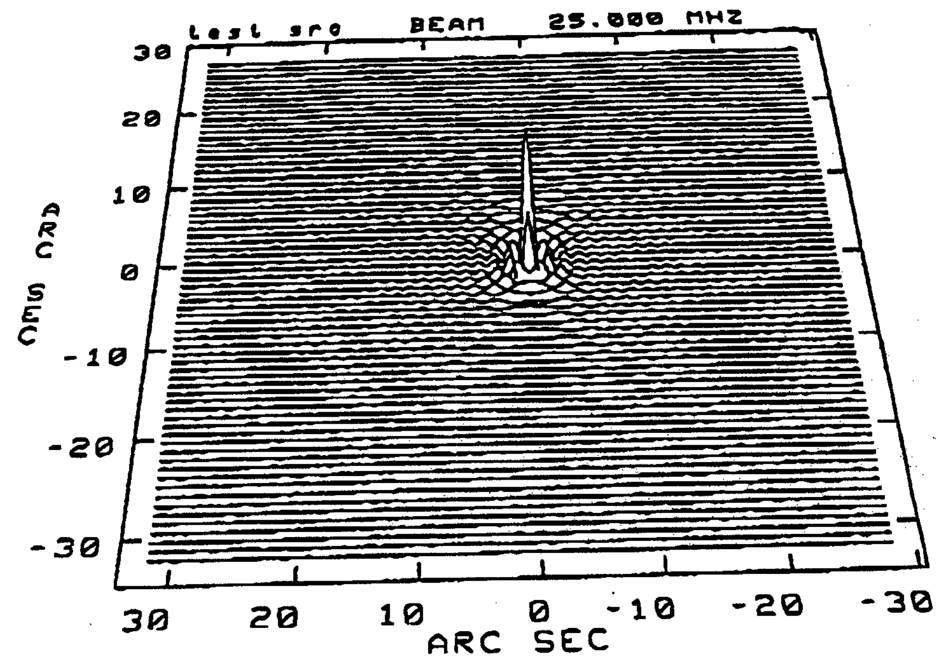
- Low Frequency telescopes are:
  - simple
  - low mass (100 kg per telescope)
  - relatively low cost ($10M-$20M, excluding launch; i.e., University Explorer category)
- Long baselines between orbiting telescopes will produce arcsecond resolution at 25 MHz (factor of 100 improvement over best LF ground-based observations to date).
- Two orbiting telescopes relatively quickly sweep out (u,v) plane to produce good dynamic range images. (Details depend upon siting which will be determined from OHFRIM).
- Can explore one of the last unopened windows down to 1 MHz.
- Nonthermal sources are very bright at low frequencies.

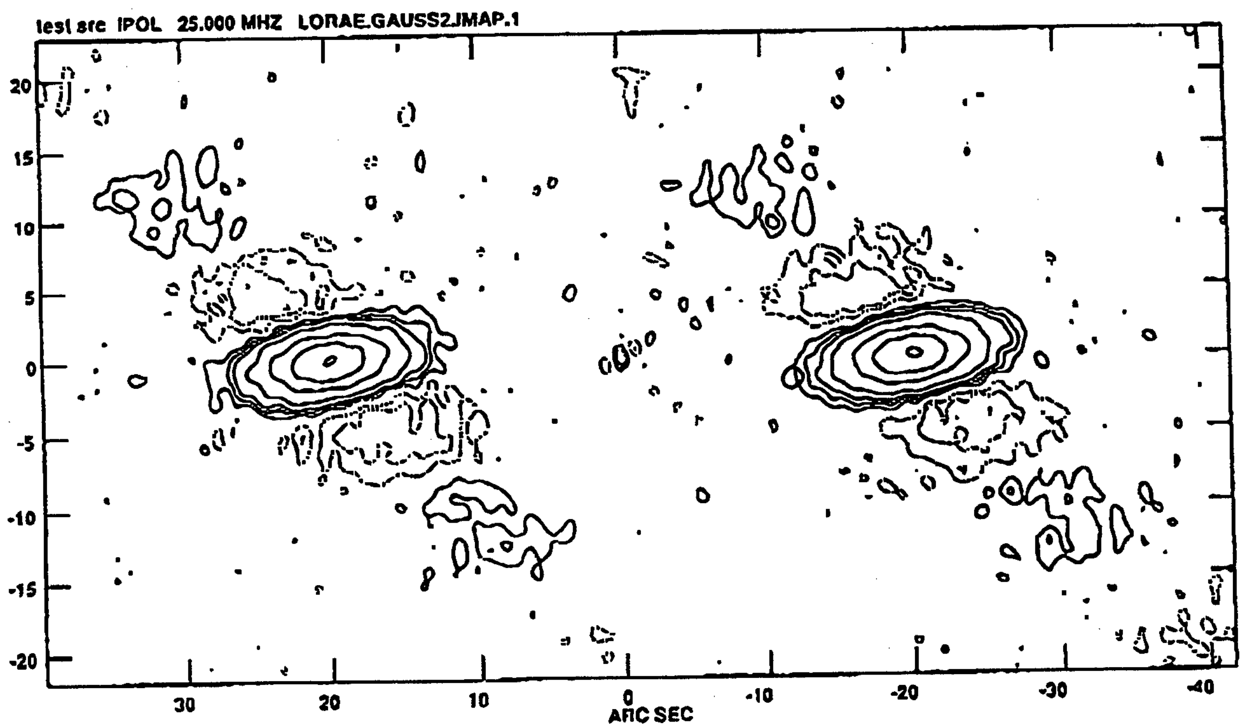
uv-PLANE COVERAGE

- Two satellites, orbital planes 90° apart
- Orbital radii: 100 and 110 km
- Source Coord: R. A. = 7 hrs., Dec = 35°
- uv points excluded if both satellites were in view of the Earth



SIMULATED MAP



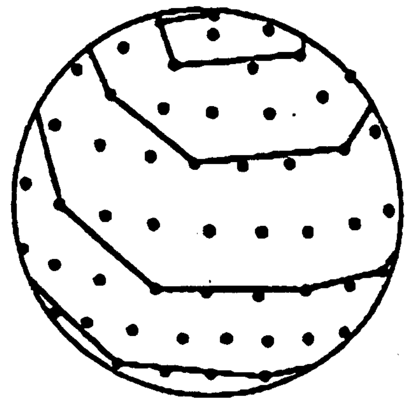


CENTER AT RA 00 28 0.000 DEC 35 00 0.00
Peak flux = 6.1840E+01 JY/BEAM
Levs = 3.0000E+00 * (-2.00, -1.00, 1.000, 2.000, 3.000, 5.000, 10.00, 15.00, 20.00, 25.00, 30.00, 40.00, 50.00)

TELFI Telescope Design

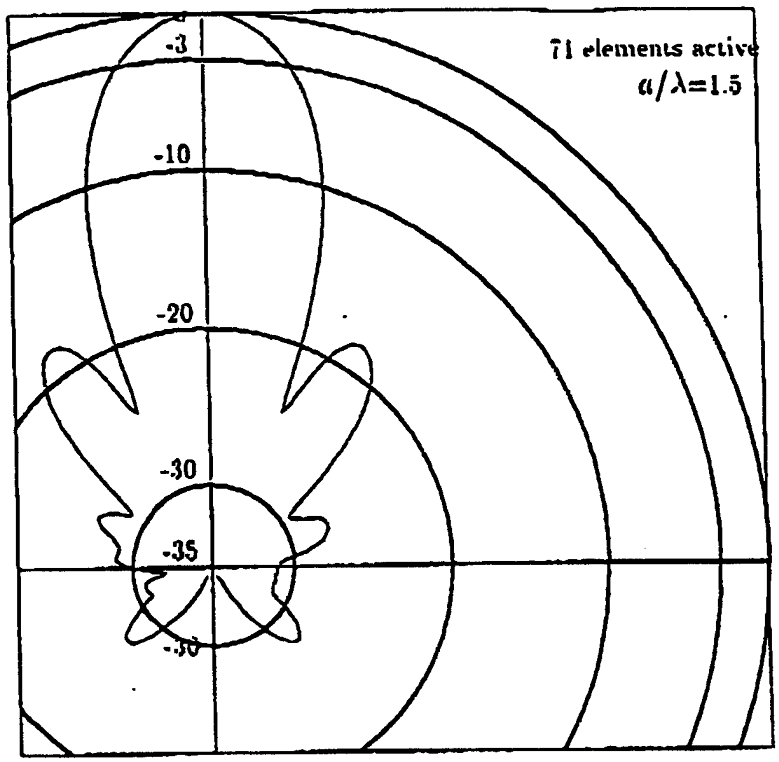
- Each spacecraft contains an inflatable phased-array spherical antenna with 150-200 elements.
  - antenna is 10-20 m in diameter.
  - enormous improvement in directivity (200x) and sensitivity (200 mJy/beam in 10^6 sec) over a simple dipole.
  - can point antennas at several different locations at the same time via subarray phasing.
  - no moving parts.
- TELFI will operate from 1-25 MHz.
- Baseline calibration performed at 150 MHz.
- Standard superheterodyne VLBI receiver with crystal oscillator clock; use VLBA correlator.

ANTENNA



- Spherical array
- Elements placed symmetrically on latitudinal rings
- Natural taper
- Elements and T-lines plated on Kevlar balloon
- Grouped phase shifters (minimal number)
- Minimal beam swinging
- Identical beams for beams above nodes
- Example: 162 elements placed on 13 rings
  71 active elements at one time

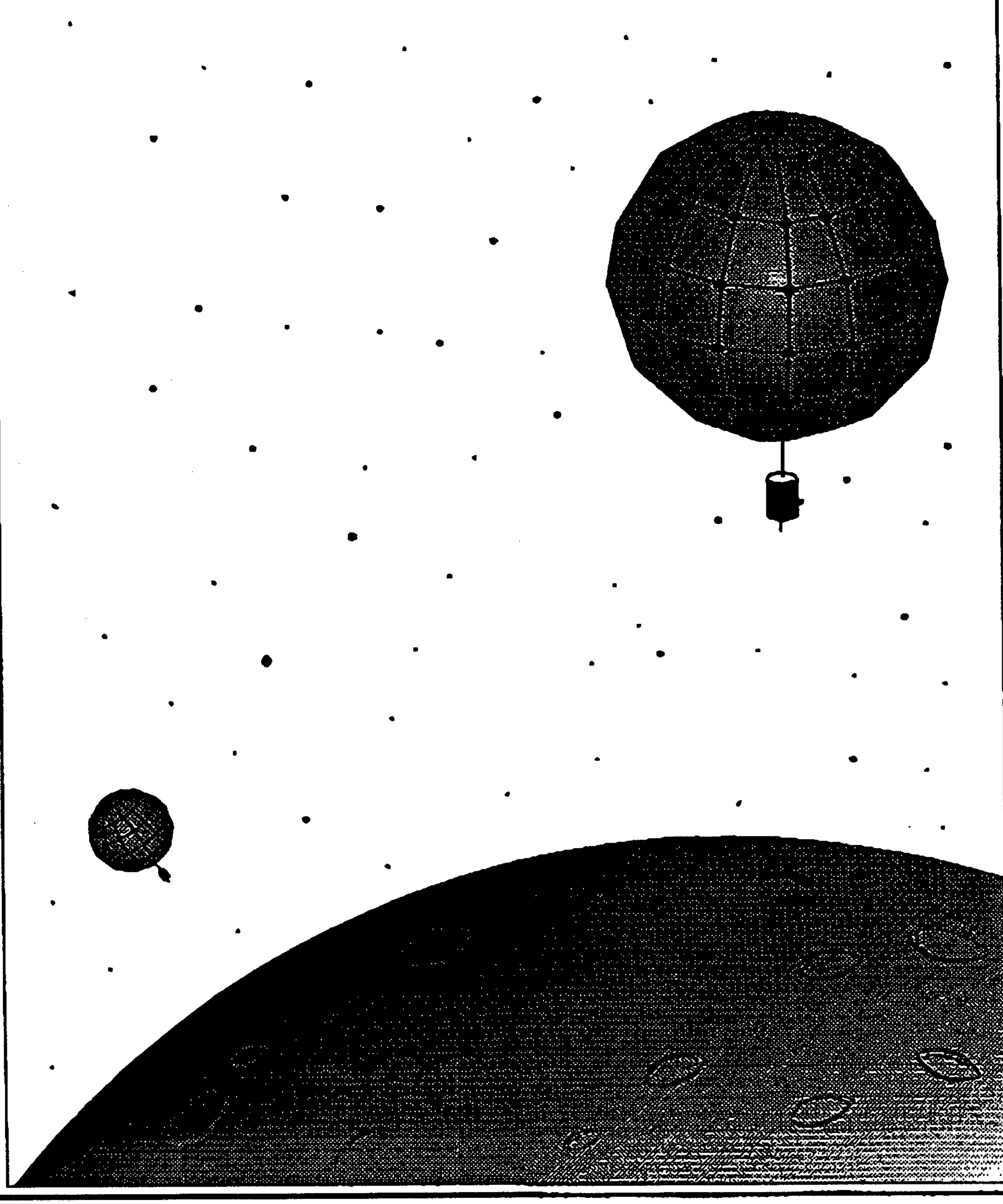
ANTENNA PATTERNS



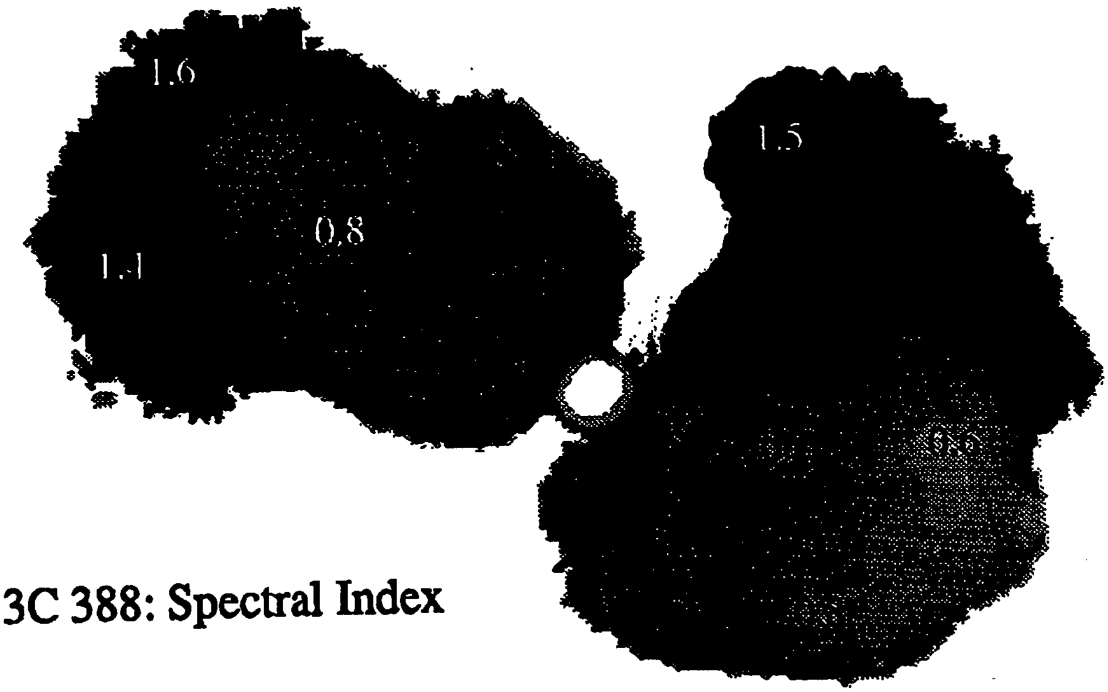
On-axis beam

a/λ=1.5, HPBW =20$^{\text{O}}$, D=23 dB, -18 dB sidelobe

TWO-ELEMENT LOW FREQUENCY INTERFEROMETER (TELFI)

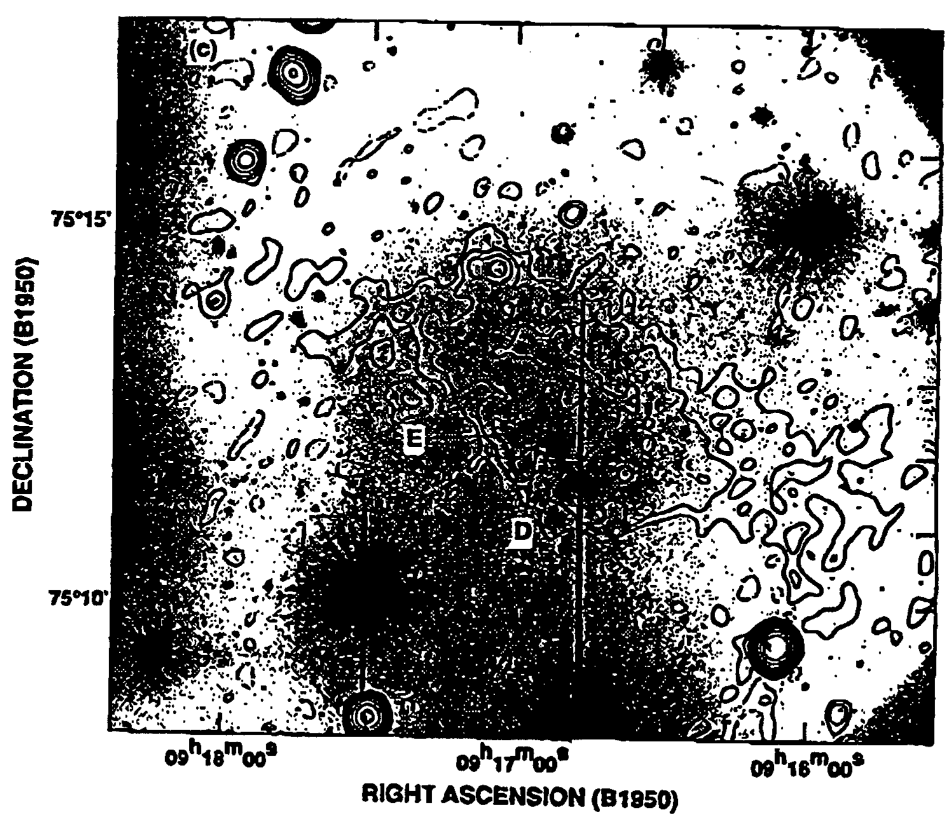


A Science Highlight with TELFI: Imaging Steep-spectrum "Relic" Radio Emission from AGNs & Galaxy Clusters



3C 388: Spectral Index

K. Roettiger, J. O. Burns, D. Clarke, W. Christiansen



VLA 20-cm image (15" resolution) of steep spectrum relic radio source in a poor group (Harris et al. 1993, AJ)

Summary

- The LF radio astronomy community is proposing an evolutionary approach for Low Frequency Astrophysics from Space:
  - Begin with a precursor mission, OHFRIM, which will measure the LF noise environment & test technologies (e.g., inflatable antenna).
  - TELFI will map stronger, extended sources from 1-25 MHz with up to 1" resolution.; possible technology spin-off for communication antennas.
  - Multielement array in orbit.
  - Lunar surface arrays.
- Exciting & unique science at low frequencies - origin & evolution of cosmic rays & magnetic fields.
- Strong student involvement in both engineering & data analysis.

V. AstroTech 21 Test-Beds

[Material for this section has not yet been prepared.]